REPUBLIC OF TURKEY
ADANA SCIENCE AND TECHNOLOGY UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF NANOTECHNOLOGY AND ENGINEERING SCIENCES

ENERGY, EXERGY AND EXERGOECONOMIC ASSESSMENT OF A COGENERATION SYSTEM IN FOOD INDUSTRY

ARZU PEKDUR

MSc THESIS

SUPERVISOR

ASSOC. PROF. DR. N. FİLİZ ÖZDİL

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Approval of the Graduate School of Natural and Applied Sciences

Director

Assoc. Prof. Dr. Osman Sivrikaya

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

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İmge

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ENERGY, EXERGY AND EXERGOECONOMIC ASSESSMENT OF A COGENERATION SYSTEM IN FOOD INDUSTRY

PEKDUR, Arzu
Master of Science, Department of Nanotechnology and Engineering Sciences
Supervisor: Assoc. Prof. Dr. N. Filiz ÖZDİL
June 2018, 58 pages

ABSTRACT

The study carries out a comprehensive analysis of the first and second law of thermodynamic through their application to 14.25 - MW cogeneration system at the city of Adana, in Turkey. The cogeneration structure comprised a turbine, a boiler, an economizer, a ventilation fan, a pair of pumps, and a chimney. Although the energy requirement for customer was established to be around 10.5 MW, the cogeneration system exceeded the amount requested by the customer and generated roughly 1.35-fold of the originally requested energy. The way the energy and exergy efficiency values are influenced by the members of the system and the functions of the components were analyzed separately to obtain information about the performance of every component individually. The findings showed that boiler had the highest irreversibility with an irreversibility value equaling to 36% of the irreversibility of the entire system, which is attributable to the structure of a boiler. In addition, with a 34% and 25% contribution to the irreversibility of the entire system, respectively, the irreversibility values of the economizer and chimney were notably high. In addition, the study focused on the relations between the steam pressure at the boiler output and energy and exergy efficiency. The investigation of hereby relationship revealed that exergy destruction of the boiler decreased with increasing steam pressure at the boiler output, which leads to increased boiler efficiency. Furthermore, the results showed that combustion efficiencies of the cogeneration structure reached satisfactory levels due to the high molar fraction of the CO_2 at the chimney output.

__Keywords:__ Energy, Exergy, Thermodynamic analysis, Exergoeconomic, Cogeneration systems.

GIDA ENDÜSTRİSİNDE KOJENERASYON SİSTEMİNİN ENERJİ, EKSERJİ VE EKSERJİEKONOMİK DEĞERLENDİRMESİ

PEKDUR, Arzu

Yüksek Lisans, Nanoteknoloji ve Mühendislik Bilimleri Anabilimdalı

Tez Yöneticisi: Doç Dr. N. Filiz ÖZDİL

Haziran 2018, 58 Sayfa

ÖZET

Bu araştırmada, Adana'da bulunan 14.25 MW kojenerasyon sistemine uygulanan birinci ve ikinci termodinamik kanunların kapsamlı analizi yapılmıştır. Kabul edilen kojenerasyon sistemi türbin, kazan, ekonomizer, havalandırma fanı, iki pompa ve bir bacadan oluşmaktadır. Fabrikanın kendi enerji ihtiyacı yaklaşık 10.5 MW iken kojenerasyon sisteminde ihtiyacın neredeyse 1.35 katı üretilmektedir. Enerji ve ekserji verimliliği üzerine her bir sistem unsurunun görevi ve etkisi, her bileşenin tekil performansı hakkında bilgi edinmek için analiz yapılmıştır. Çalışma sonuçları, maksimum tersinmezliğin kazanda gerçekleştiğini ve bunun da sistemin tamamının tersinmezliğinin % 36'sı olduğunu ve bu tersinmezliğin sadece kazanın doğasından kaynaklandığını belirtmek için önemlidir. Buna ek olarak, ekonomizer ve baca, sırasıyla,% 34 ve% 25 olan daha belirgin tersinmezliğe sahiptir. Bu tezde kazanın çıkışındaki buhar basıncı ile enerji ve ekserji verimi arasındaki ilişki de araştırılmıştır. Kazan çıkışındaki buhar basıncı yükseldiğinde, kazanın ekserji tahribatının azaldığı vurgulanmaktadır; bu sebeple kazanın verimliliği artmektadır. Buna ek olarak, bu kojenerasyon sisteminde baca çıkışında yüksek molar fraksiyon değeri bulunduğu için tatmin edici bir yanma verimi olduğu ortaya çıkmaktadır.

Anahtar Kelimeler: Enerji, Ekserji, Termodinamik analiz, Ekserjiekonomik, Kojenerasyon sistemleri.

ACKNOWLEDGEMENTS

Firstly and above all, I’d like to present my thanks to my supervisor Assoc. Prof. N. Filiz ÖZDİL regarding worthful pathbreaking & encouragement. Furthermore, she also gives me a source of inspiration to study this thesis, the ambition to motivate me greatly contributed to my thesis.

In addition, I would like to thank to my Research Assistant friend Atakan TANTEKİN at Adana Science and Technology University for his friendship and moral support.

Finally, I am greatly indebted to my mother Mesrure GÜRGEN, my aunt Berrin DEMİRALAY who interested my baby when I was at school. I also thank to my beautiful daughters, Eylül and Deniz whom I did not care enough during my studies. And special thanks for my lovely husband Hikmet PEKDUR for his encouragement and support.

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NUMENCLATURE

$\overline{C}_p$	specific heat capacity (kJ/kmolK) Cp
$\overline{\dot{m}}$	molar flow rate (kmol/s)
E	energy rate (kJ/sn)
ex	specific exergy (kJ/kg)
$\dot{E}x_D$	Exergy Destruction (kW)
h	specific entalpy (kJ/kg)
LHV	lower heating value of coal (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
$\dot{Q}$	rate of heat transfer (W)
s	specific entropy (kJ/kg K)
T	temperature (K)
$\dot{W}$	rate of work (W)

Subscripts

AF	aspiration fan
CH	chimney
cg	combustion gas
destr.	destruction
ECO	economizer
ng	natural gas
P	Pump
TE	Turbine
VF	Ventilation fan
0	reference state

Greek symbols

η_I	first law efficiency
η_{II}	second law efficiency

CHAPTER 1. INTRODUCTION

Energy is critically noteworthy issue throughout the world coupled with the reduction of fossil fuel and environment pollution. Fossil fuels are currently the leading energy source worldwide, albeit the finite fossil fuel resources. This poses the threat of energy poverty. Therefore, studies have taken on the task to solve these problems simultaneously through two means:

i. Developing and using alternative energy sources (particularly renewable energy sources)
ii. Improving the energy efficiencies in the fossil fuel-using equipment/systems

The fossil fuels are among the main causes of environmental pollution, whereas natural gas is an environmentally-friendly alternative. Not using fossil fuels and, hence, not contributing to global warming render heat recovery one of the most viable sources for energy production. The waste heat recovery process contributes both to the conservation of energy and abatement of thermal pollution. It is also used to heat buildings, preheat the plant processes, and produce electricity. Figure 1.1 displays the diagrammatic representation of the dispersion of the energy sources of electricity production in Turkey, 2017.

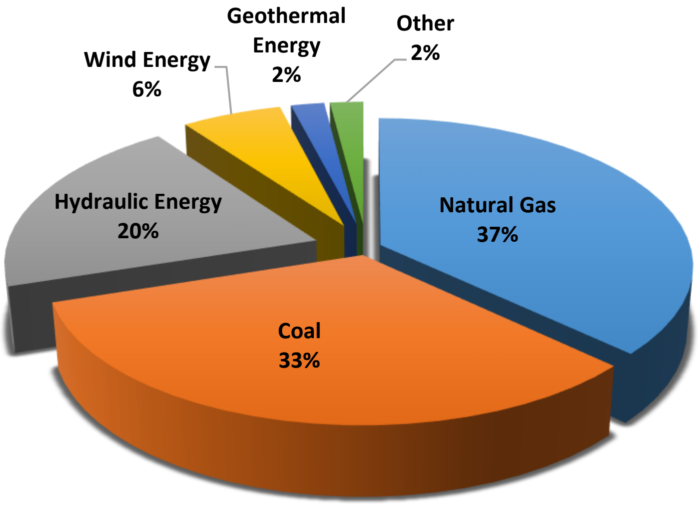

Figure 1.1. Diagrammatic representation of the dispersion of the energy sources of electricity production in Turkey (Anonymous, 2017)

Cogeneration is the successive generation of two different useful energy forms based on a main energy source. The energy can either be electrical and thermal or mechanical and thermal and the sequences of generation can include any combination of these energy forms. It is well-known for its high energy efficiency and provides two of the required energy forms in the same quantity as each other in addition to its advantage in minimizing the primary energy cost. It meets the same power and heat requirements as a conventional energy supply system by consuming significantly lower amounts of primary energy than does a conventional system in which power and heat are produced separately. The combined production feature of cogeneration reduces the production costs of the economies of scope and emerges as a critically important criterion to consider in improving the efficiency of the currently available cogeneration systems. Cogeneration produces heat and work through the use of a single fuel to meet the energy use of a system. Cogeneration systems result in increased energy efficiency and decreased environmental pollution. Moreover, increasing the efficiency of systems is cost-friendly, rapid, and easily applicable. Thus, the analysis of the performance, especially the effective loss and irreversibility analyses, is of fundamental importance in the improvement measures. Within this scope, exergy term and exergy analyses have become vital. Exergy analyses are an indispensable tool to design, analyze, and optimize thermal systems. Its application to an extensive range of energy systems has been successful. It provides necessary information when choosing a suitable component design and operation procedure. The information provided by exergy analysis contributes much more greatly to the evaluation of plant and operating expenses, fuel resourcefulness, and pollution. In addition to its potential for improving the energy efficiency of systems, exergy analysis enables the description of the enormities and localities of exergy destructions (irreversibility) inside the entire system. Figure 1.2 shows the diagrammatic representation of a cogeneration process and Figure 1.3 shows the diagrammatic representation of the sectoral distribution of cogeneration systems in Turkey.

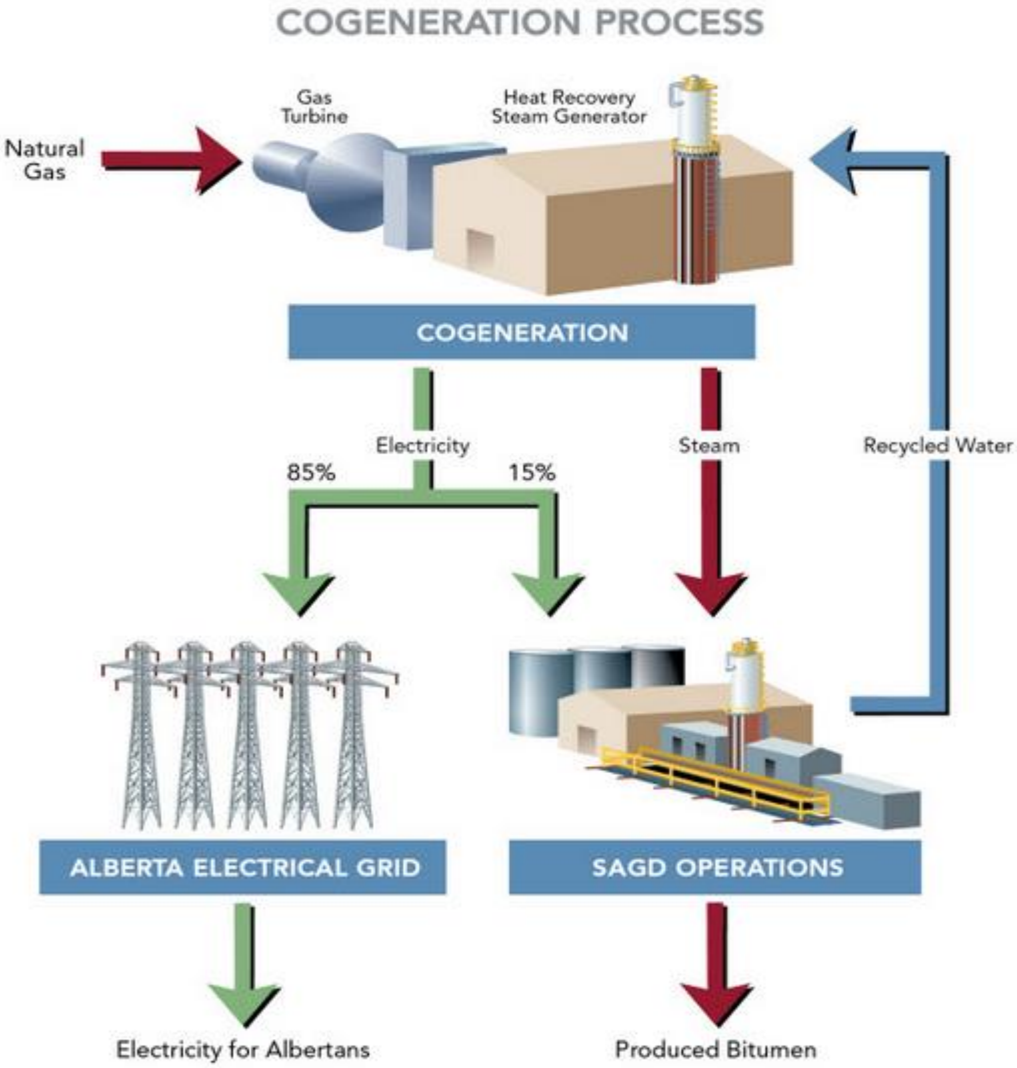

Figure 1.2. Diagrammatic representation of a cogeneration process (Anonymous, 2017)

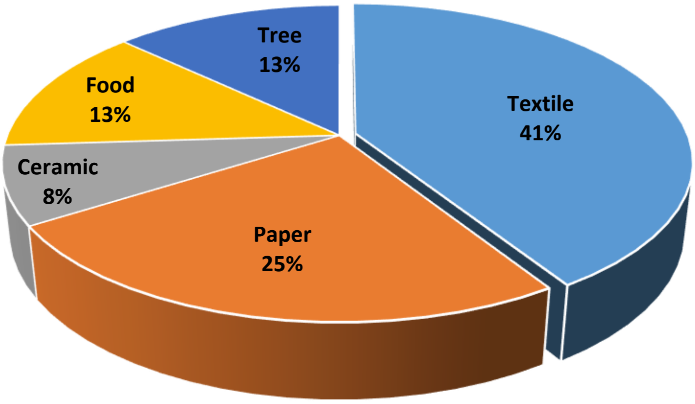

Figure 1.3. Diagrammatic representation of the sectoral distribution of cogeneration systems in Turkey (Anonymous, 2017)

Cogeneration is among the most important methods in the efficient use of fuels along with its contribution to the savings in natural and financial resources and protection of the environment. Various countries have taken on the task to overcome the obstacles arising out of its use and promote its widespread use. The relatively high prices of the surplus power purchases from power corporations and investment subsidies are among the implementations to promote its use. Cogeneration systems having reciprocally working internal combustion engines are divided in three categories: (a) small scaled unit with gas or diesel engine, (b) moderate size capacity systems (1000 – 6000 kW) with diesel or gas engine, and (c) high capacity system (higher than 6000 kW) with diesel engine. Diesel engine can be classified under three categories; ‘‘high-speed”, ‘‘medium-speed”, and ‘‘low-speed”. Most of the distillates of the oil are considered appropriate for use as fuels and relatively heavier oil distillates are utilized in engines with a larger size. The Turkish private power manufacturing sector uses diesel engine plants in regions without a natural gas supply. Diesel engines have certain advantages such as shorter installation periods, higher levels of efficiency, and more power to heat ratio than those of other main mover elements including steam or gas turbines. Using the heat from the engine and energy of exhaust gases, the diesel engine-powered cogeneration systems supply the hot water and steam requisite of manufacturer sites. Figure 1.4 shows the diagrammatic representation of a cogeneration plant.

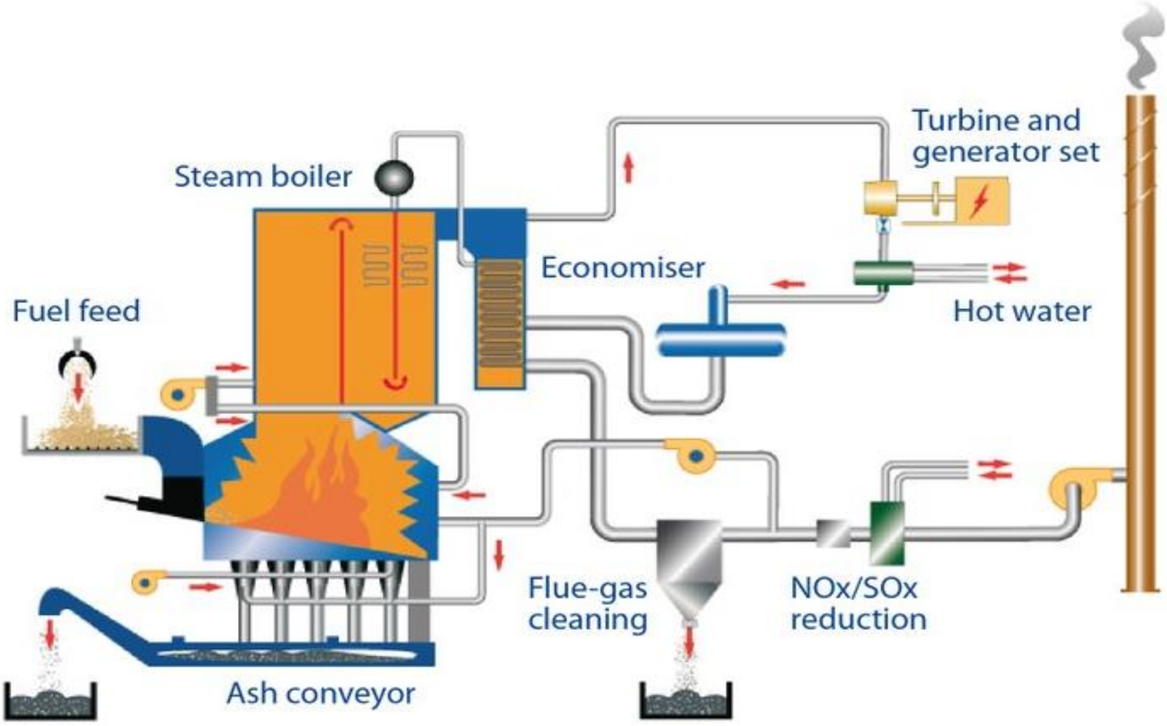

Figure 1.4. Diagrammatic representation of a cogeneration plant (Combined Heat and Power) (Anonymous, 2010)

Thermodynamic can be described as study of the relationships of heat, work, temperature, and energy. In a broader context, thermodynamic is concerned about the conversion of energy from and to other forms of energy and the transfer of energy from one location to another. Accepting heat as an energy form that corresponds to a definite value of mechanical work is the most fundamental concept of thermodynamics. Figure 1.5 shows the diagrammatic representation of the thermodynamic laws.

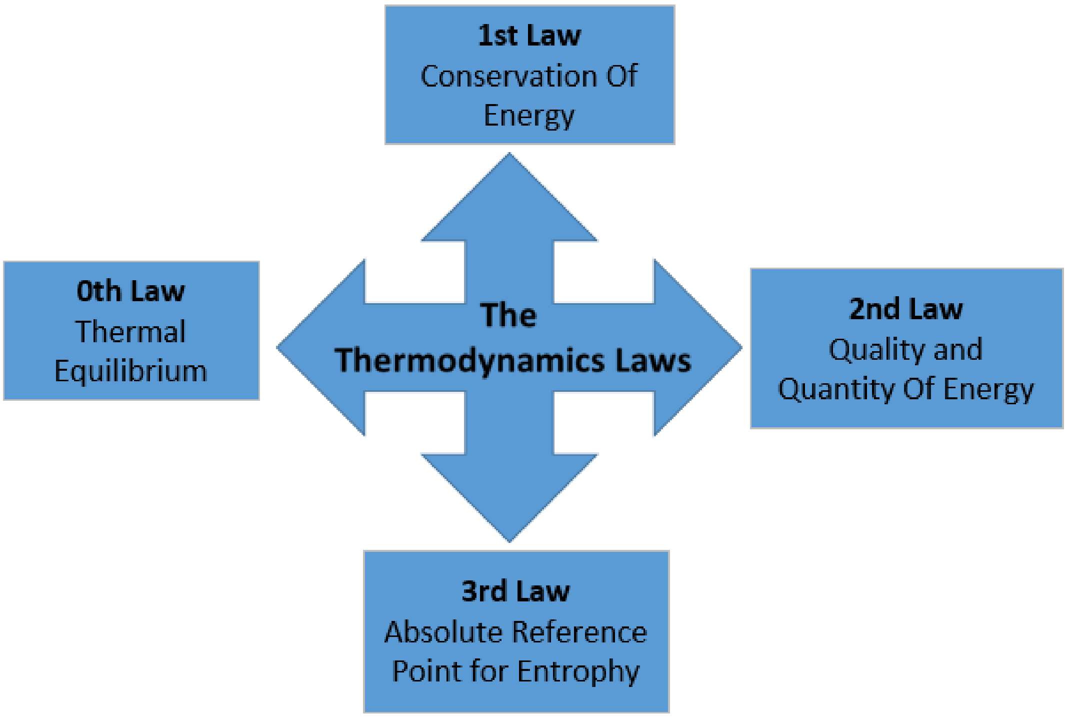

Figure 1.5. Diagrammatic representation of the thermodynamics laws

The fundamental laws of thermodynamic are:

i. *The 0th law of thermodynamic.* Two systems are in thermal equilibration where both systems are in thermal equilibration with a third system. This property allows use of thermometers as a “third system”, can be described “a temperature scale”.

ii. *The 1st law of thermodynamic.* Distinction between the heat entering to the system from the ambient and the work made by the system to its surrounds equals to the change in the internal energy of system.

iii. *The second law of thermodynamic.* The flow of heat from a less warm region to a hotter region is not spontaneous, or, correspondingly, the complete conversion of heat into work is not likely at a given temperature. Thus, heat energy per unit temperature or the entropy of a closed system gradually rises towards a maximum value. Thus, all closed systems are disposed to reach an equilibrium state, which is a state of maximum entropy in which the energy required to produce useful work is not available. The asymmetry between forward and backward processes leads to the asymmetry of time, which is also denoted as “arrow of time.”

iv. *The 3rd law of thermodynamic.* The entropy of a crystal of an element in its steady phase has a tendency for reaching zero as the temperature approximates absolute zero, which, from a statistical point of view, allows establishing an absolute scale for entropy to determine the degree of randomality or irregularity in a system.

The need for optimizing the performances of steam engines brought about the rapid development of thermodynamics during the 19th century but the all-embracing applicability of the laws of thermodynamics to physical and biological systems renders their use all the more prevalent. The laws of thermodynamics describe the modifications in the energy state of a system and the ability of the system to do beneficial work on their environments.

Exergy is measured as potential of a stream to give rise to a change, stemming from the deviation of the stream from complete stability in terms of a reference environment. It is described as the maximum work producible by stream of matter, heat, or work as the stream reaches equilibration with a referred environment.

Exergoeconomic analysis can be described as a mixture of the exergy and economic analyses and has a great potential in the optimization of the systems through the use of the efficiency of energy and exergy. The goals of exergoeconomic analyses include: (Ozdil and Tantekin, 2017)

i. Separately calculating the expenses of each produced item generated by a multi-product system,

ii. Giving an insight into the expense formation procedure and the flow of the expenses in a system,

iii. Separately optimizing specific parameters regarding the components, and

iv. Optimizing the overall system.

CHAPTER 2. LITERATURE REVIEW

Bade and Bandyopadhyay (2015) stated that combined heat and power (CHP), is of importance both for improvement of the energy efficiency of entire plant and reduction of environment pollution. The researchers proposed a pinch analysis-based method in which a gas turbine and a regenerator were combined with a process plant to decrease fuel consuming to minimum. In the study, a methodology was introduced to directly integrate a gas turbine and regenerator inside the process plant. Related results revealed that the optimum pressure ratio to achieve the highest value of power plant efficiency was less than the limit pressure ratio at which the net-work reaches its highest value. Thus, the researchers concluded that a compromise between the efficiency of gas turbine plants and size and weight may be necessary. They emphasized that a gas turbine power plant designed to obtain maximum power plant efficiency at an optimum pressure necessitated the use of a maximum specific network-producing system, a high compressor ratio, and a low power plant efficiency in addition to requiring larger sizes and capacities because of its lower specific clearance.

Bonnet et al. (2005) argued that hot-air engines (Stirling and Ericsson engines) were highly appropriate to use in micro cogeneration because of their noiseless operating conditions and low maintenance requirements. Ericsson engines (in other words, external heat-supplied Joule-cycle reciprocating motors) are more interesting because their designs are less restricted and potentially cheaper than Stirling engines, and they have shown that they provide better systems for energy. They have examined the relationship between the Ericsson engines and a natural gas combustion system. The conventional energy, exergy, and exergoeconomic analysis were made to design the system. Researchers presented the results they obtained from the analyses and their evaluations for the cost of the cogeneration system. The energy analysis performed in the study helped the designing and dimensioning of the plant and allowed the testing of the effects of heat exchangers on the productivity and cost for raw materials. The researchers noted that the proper evaluation of the activity of each heat exchanger was important in obtaining better efficiencies, avoiding large transfer surfaces, and minimizing costs. The analyses allowed finding an appropriate compromise among efficiency, heat transfer area, and heat exchanger costs. Through the exergy research, a diagram was drawn and the exergy flows and exergy destruction in the system were observed. The study aimed to shed a new light on an old, yet cost-friendly, easy, and productive technology and invigorate the Ericsson engine that faces undue negligence.

Orhan et al. (2009) investigated the production of core-based hydrogen through thermochemically obtained water separation utilizing a copper-chlorine (Cu-Cl) cycle in which water is separated to hydrogen and oxygen after some chemical reaction. The cycle comprises five phases including three thermal and an electrochemical reactions: (1) production of HCl (g) using equipment such as fluidized beds, (2) O_2 production, (3) Cu production, (4) drying, and (5) hydrogen production. Each section involves a chemical reaction, except for the drying process. In this study, production of HCI (g) and the effects of its operation and environment states on the Cu-Cl cycle were described; comprehensive thermodynamic analysis was performed using the related chemical reaction. The performance of the fluidized bed was investigated using energy and exergy efficacies in addition to the parametric studies in which different reactions, reference ambient temperatures, and energetic and exergetic angles were used. Parametric studies yielded information about the effect of the reaction temperatures and the referred ambient temperature values on the reaction heat, entrance and exit gas, exergy destruction, and exergy efficiency. To obtain lower product expense and improve the monetary practicability of the process, the researchers recommended using the outcomes taken from energy and exergy analysis in exergoeconomic analysis and optimization of process.

Nemati et al. (2017) compared the Organic Rankine Cycle (ORC) and Kalina Cycle (KC) with each other using thermodynamic modeling and optimization to reveal their advantages as bottoming cycles for waste heat recovery in CGAM cogeneration systems. The models were developed for the CGAM / ORC and CGAM / KC systems and the effect of certain decisive factors on energy and exergy yield and turbine dimension parameters were examined. The results showed that the optimization of the 1st and 2nd law efficacies at a certain pressure ratio and the minimization of the bottoming cycle net output power and TSP were achieved through changing the air compressor pressure ratio. An increase in the temperature of the pinch spot reduced the energy and exergy efficacies, cyclic power generation, and TSP. The energy and exergy efficacies, energy production, and TSP increased with increasing concentrations ofammonia in the circulation. The energy and exergy efficiencies of the CGAM / ORC system was higher than those of the CGAM / KC, indicating that ORC is preferable over KC in the waste heat recovery from CGAM.

In their study, to evaluate the yield composition of a biomass gasification system utilizing extremely pre-heated air and steam, Wu et al. (2014) developed a chemical equilibrium model and discussed the advantages and limitations of the system in terms of thermodynamics. The analysis of the first and second law of thermodynamic were performed for different pre-heating temperature and steam / biomass mass (S / B) ratios. Under these conditions, the highest chemical energy output from the obtained synthesis gas was maintained when the S / B ratio was 1.83 but as the S / B ratio increased, so did its negative effects on the energy and exergy efficiencies. The researchers determined that chemical energy and energy and exergy efficiencies increased with increasing preheat temperatures and the highest values of energy and exergy efficiencies were 81.5% and 76.2%. In view of the highest values obtained for the efficiencies, Wu et al. identified a possible thermodynamically probable study area and proposed a practical study area for industrial applications.

Kumar (2017) provided an insight into the opportunities for future research on thermal power plants. The researcher asserted that the increasing energy supply-demand has drawn attention to the efficiency of the equipment and the optimization of existing thermal power plants. Kumar stated that the energy balance of the system is not always sufficient to detect system inadequacies and energy losses occurring in a system may easily be detected by an exergy analysis. The researcher pointed to exergy analysis as a capable tool for measuring energy quality and stated that it can help increasing the efficiency of complex thermodynamic systems. The studies in which the thermodynamic analysis of Rankine cycle in coal-fired power plants was performed have revealed that highest energy loss had occurred in the condenser. Great excavation was found on the damage. The studies have also explained that the cost of the exergy destructions in boilers and turbines was greater than that of the exergy destructions in other components. In the studies carried out in gas-fired power plants, the burners were determined to have the lowest efficiency and pointed out as the largest exergy destructor. Using both classical and exergetic analysis, the combustion chamber was determined to be responsible for the highest exergy destruction. Since supercritical, ultra-supercritical, and advanced super critical cycles have not been much focused on energy and exergy analysis until now, since gambling, material used cannot withstand very high pressure and temperature.

Can et al. (2009) examined exergy and economic analysis based on the values acquired during the study period of a cogeneration facility system in Turkey. The first and second laws of thermodynamics have been modified to the measured values to find the fuel efficiency, power-to-heat ratio, and process heat ratio. The system is thought to be a stable state open system. Conclusively, efficiency of second law was 89.5% and the payback duration of the facility was 3.5 years. These values are the appropriate efficiency and time interval for good designed plants from the perspective of economic analyses. Can et al. have obtained the result that the installation of cogeneration system may find more industrial utilization because of the reduction of energy and oil reserves in the future.

Puadian et al. (2014) developed an integrated system model for a rotary biomass dryer utilizing a combined use of a dual-fluidized bed (DFB) biomass gasifier and user-defined and internal unit operations at UniSim Design. A quasi-equilibrium model was employed to model the biomass vaporization gasification in the DFB gasifier. The energy and mass balance, dryer configuration and heat transfer were used to simulate the biomass. Following the evaluation and validation of the model using the experimental data, the model was used in the investigation of the impact of the steam to biomass (S / B) rate and the gasification temperature on the gasification implementation and the impact of the air fed to the fast fluidized bed (FFB) reactor and biomass humidity content on the combined system capacity. The results revealed that the gasification warmth and the S / B ratio positively affected the gasification efficiency. Puadian et al. reported that a higher air procurement to the DFB gasification was relatively favorable if the drying biomass had higher moisture content, which is attributable to its increased requirement for flue gas, however flue gas at a lesser temperature was suitable for use in the biomass dryer. Thus, more steam with a higher combustion gas rate is produced and energy efficiency is not much influenced as opposed to the decrease in exergy, which is due to the considerably lower exergy of the excess fuel than that of the steam produced in the system.

Yildirim and Gungor (2012) stated that the exergoeconomic analysis was among the most prevalently used exergy sub-methods in which exergy analyses and economic analyses are combined. Considering a prior exergetic analysis of a CHP system with a aggregate electric power of 11.52 MW and steam generation capacity of 9.0 ton / h at 140.5C, the researchers proposed a suitable location for cost-based information and CHP system enhancement. An analysis based on the Specific Exergy Costing (SPECO) methodology was performed and the calculations showed that the specific unit exergy cost of the electricity generated by the CHP system was US Dollar 4.48 / GJ. The study revealed that the information provided by the exergoeconomic analysis was more extensive than that by the exergy analysis and could offer exergoeconomic locations suitable for the improvement of the CHP system, which, in turn, will escalate total efficiency of the system through the identification of the main loss sites and thereby obtaining an optimized process.

Özdemir et al. (2010) conducted an exergoeconomic analysis adopting actual operational data based on a fluidized-bed coal combustor (FBCC) steam power plant in İzmir, Turkey. The sub-systems of the plant include a ventilation fan (VF), a FBCC, a heat recovery steam producer (HRSG), a cyclone (CY), an economizer (ECO), an aspiration fan (AF), a pump (P), and a chimney (CH). A comprehensive exergoeconomic analysis study has been conducted with FBCC steam plant's basic subsystems including VF, FBCC, HRSG, CY, ECO, CH, and P. The researchers stated that, as an analysis yielding cost-based information, the exergoeconomic analysis provided more information than the exergy analysis. The researchers recommended placing an air preheater factory among the VF and FBCC for the minimization of the utilization of exergy in FBCC.

Gurturk and Oztop (2016) performed the energy and exergy analysis of a cogeneration facility. The most important component in the cogeneration power plant was a circulating fluidized bed boiler (CFBB), also a steam generated by the cogeneration power unit was utilized in salt manufacturing. The CFBB had an energy yield and exergy yield of 84.65 % and 29.43 %, while the mean exergy yield of the boiler was 43.58%. The exergy yield of CFBB was relatively lower than that of similar boilers. The exergy damage of the CFBB was determined to be 21789.39 kW and equaled to 85.89% of the exergy damage in the CFBB. Using fuels with low combustion efficiency resulted in increased entropy production. Moreover, the balance ratio and combustion yield of the CFBB were calculated to be 1.053 % and 69 %. The power plant had an exergy efficiency of 20%. The analysis results revealed that optimization was required for the CFBB in addition to the need for the re-evaluation of certain design parameters.

Kamate and Gangavati (2009) evaluated the exergy analyses of the heat-matched, bagasse-based cogeneration plant of a 2500 tcd (tons of cane per day) sugar factory in which a back-pressure steam turbine and subtraction condensing steam turbine were used. Coupled with more general energy analyses, total and component efficiencies were evaluated using the exergy methods along with the determination of thermodynamic losses. A boiler with contemporary properties can only use 37 % of the chemical exergy of the fuel in steam production and the boiler-related combustion irreversibilities are lost by 63%. Hence, exergetic efficiency of the boiler is open for improvement. Moreover, the exergetic efficiency of the boiler improves significantly with increasing input conditions of the HP steam. Therefore, steam production temperature and pressure can be increased to minimize exergy losses and improve exergetic efficiency.

Ozdil and Tantekin (2016) conducted a study to provide an elaborate exergy and exergoeconomic analysis of an electricity generation system using biogas engine in a treatment of wastewater plant in the city of Adana. The system comprised a compressor, a turbine, four heat exchangers, a pump, and a gas engine. How the exergic and exergoeconomic parameters of the system were affected by the components was investigated separately for each component. The results revealed that the highest exergy destruction was 4055.31 kW and occurred in the gas engine, followed by the exhaust gas heat exchanger (EGHE) and lubricating oil exchanger (LOHE) with exergy destruction values of 99.86 kW and 92.64 kW, respectively. Exergy efficiencies of compressors, turbines, pumps, BGHE, LOHE, WHE, EGHE, and gas engines were determined to be 76.50%, 78.43%, 6.49%, 13.40%, 11.56%, 60.44%, 67.36%, and 50.79 %. The exergy destruction rate was 4341.03 kW, while the exergy efficiency of the plant was 69.10%. The researchers mainly attributed the inadequacy of the system to the high temperature differences in chemical reactions occurring in burnout process, the amount of excess air, the sort of biogas, heat exchangers, and high levels of heat release by the chemical reactions in the combustion process leading to increased irreversibility in the system. An excessive increase in the air causes increases in mass flow rate of combustion gas, which results in increased heat loss in the system and, thus, decreased efficiency. The change in the biogas content used in the gas engine results in varying proportions of exergy destruction because of the different calorific value of the fuels as well as causing high temperature variations in the heat exchangers, that also causes exergy destruction. It is proposed to reduce the temperature differences between fluids or to keep fluids used in heat exchangers at lower temperatures to reduce damage to the system. The gas engine had the lowest exergoeconomic factor by reason of the high exergy destruction rate in the engine. The researchers argued that heat exchangers with a high exergoeconomic factor entail higher operation and maintenance costs and stated that the results of the study will be of benefit to the exergoeconomic optimization of the wastewater treatment plant.

Abusoglu and Kanoglu (2009) carried out the thermodynamic analyses of a diesel engine cogeneration system located in a plant in Gaziantep, Turkey. The exergy destruction in each component was evaluated separately also the determination of the exergetic efficiencies. The thermodynamic performance of the 25.32 MW diesel engine cogeneration system with a steam capacity of 8.1 ton / hour was determined to be 44.2% and 40.7% under full load conditions. The researchers recommended using the information obtained in the study in the designing of recent energy-efficient systems and improvement of the efficiencies of the current systems. They have concluded that the results presented in the study can serve as a powerful and systematic instrument in the determination of the cost-increasing parameters and optimization of the diesel engine cogeneration systems.

Lee et al. (2014) emphasized that it is important to have a stable estimation of the power production capacity of every power plant in an electric grid, and to manage the grid in a stable manner by preventing the incompatibility between electricity demand and energy generation. This estimate also helps protect the power plant proprietors' institutions as it permits for efficacious performance watching. Using the integration of correcting curves and thermodynamic non-design modeling, the expected power output was calculated and unique two-step logic was established to forecast future power generation capacity using a measurement-based power correction factor. A logic-based simulation program has been developed and approved. The basic property of this logic is to find the power correction factor by comparing the actual power and the anticipated power output. In other words, it is significant to simulate the performance degradation using the plant's actual operation data. In general, the feasibility and practicality of the suggested method has been verified. The improved logic should be used for performance monitoring as well as electricity production capacity for electricity trading and for the identification of different types of power plants.

Gholamian et al. (2016) introduced a novel cogeneration system comprising a biomass gasifier, a gas turbine, a S-CO2 cycle, and a domestic water heater. Using the engineering equation solver (EES), the mass, energy, and exergy balances were applied to each system component and the performance of the system was simulated. The majority of the irreversibility in the system was attributed to the combustion chamber and gasifier. The parametric study showed that the pressure ratios of the gas turbine and the S-CO2 turbine significantly affected the performance of the system. Additionally, the environmental impact of the system was assessed in terms of CO2 emission by considering the system as a combination of three sub-systems: an independent gas turbine, the entire system without the water heater and the cogeneration system. The air preheater was determined to be the main contributor to the irreversibility in the system. The results obtained for the ecological effect of the system revealed that the CO2 emissions of the cogeneration system was relatively lower in addition to its better efficiency than that of the power production system and independent gas turbine.

Mert et al. (2012) conducted an exergoeconomic analyses of a cogeneration plant located in Edremit. In the research, the exergoeconomic analyses of the 39.5 MW-electricity and 80 ton/h steam generation-capacity plant was done and the mass, energy and exergy balances were implemented to the system.

Kim et al. (1998) suggested an approach for the combined exergy and thermoeconomic analysis of complex energy systems. In the study, an overall expense-balance calculation applicable to every unit of a thermal system was developed. The exergy of a material flow was divided into thermal, chemical and mechanical exergy flows and an entropy-production flow. Each exergy flow was appointed to a unit exergy cost, without regard to the type of the exergy stream and the state of the stream. Thus, a equations for unit costs of different exergies was obtained through the application of the cost-balance equation to each component and junction of the system. The equations were solved to financially evaluate the costs of different exergies (thermal, mechanical, etc.) and costs of the electric made by the thermal system. Method also allowed determining the lost costs of each component. Furthermore, as a method providing information for use in the design and operation of the cogeneration system, the exergy-costing method developed by the researchers was employed in the evaluation of a 1000-kW gas turbine cogeneration. Allocating costs for each exergy component allowed expressing the cost of the exergy of the yield for a system component with reference to other appointed exergy costs and the unit costs of added or removed exergies in the stream. The exergy-costing method provided information about the actual production process within the system. The application of the method to a gas-turbine cogeneration system revealed that the unit exergy costs increased as the production process continued and the increase in the electricity production cost was almost proportional to the input cost.

Santos et al. (2016) analyzed the biogas combustion and energy recovery processes from a thermodynamic, exergetic and thermoeconomic viewpoint. Regarding its competitive advantages and potential for extensive use, the researchers investigated whether biogas biomethanisation from the primary and secondary treatment of the activated sludge obtained from a wastewater treatment plant (WWTP) could be an option to fossil fuels as a renewable energy source. The researchers asserted that the use of biogas biomethanisation will bring about compliance with the highlights of the energy plans of the EU countries, which include the minimization of the amounts of CO2 emissions and the organic matters deposited in landfills as well as offering effective answer to reduce the environmental effect of sewage sludge. The results of the study unclosed that the majority of the irreversibility and exergy destruction was due to the process boiler. Furthermore, the exhaust gases released from the combustion chamber was determined to be economically valuable and thus, the practicality and suitability of integrating a Stirling engine into the process were investigated. The study demonstrated that creating a small-scale micro-cogeneration system was achievable and beneficial due to its contribution to sustainable waste management and energy savings in the treatment plant itself.

Uysal et al. (2017) performed the exergetic and thermoeconomic evaluation of a 160 MW-capacity power plant working with coal as source material in Turkey. The Specific Exergy Costing and Modified Productive Structure Analysis implementations were apart employed to reveal the unit exergy cost of the electricity produced by the coal-fired plant and the techniques were compared with each other. The results revealed that the exergy efficiency of the coal-fired power station was 39.89%. The boiler was determined to be the equipment with the highest potential for improvement. The unit specific exergy costs of the electricity generated by the system were determined to be 12.14 US Dollar/GJ and 14.06 US Dollar/GJwith the SPECO and MOPSA methods, respectively, which indicated that the unit specific exergy cost of electricity as determined with the MOPSA thermoeconomic technique was almost the same as the cost determined with the overall cost-balance equation for the coal-fired power plant.

Compared with other fossil fuels, thanks to the relatively longer lifetime of the coal reserves and resources, the coal-fired power plants will be of long-term benefit to the electricity production in Turkey and worldwide. Because of their contribution both to the national budget and to the reduction of air pollution and along with their longer lifetime, the assessment and development of the performance of the coal-power plants and their cost-effective operation are of great importance. In the study, a coal-fired power plant in Turkey was examined by considering each related component. As two different thermoeconomic analysis techniques, the specific exergy costing and changed productive structure analysis techniques were applied separately to the system. The exergy analysis revealed that the steam boiler and condenser were the components of critical importance in the development of the system performance.

Using the SPECO and MOPSA methods, the unit specific exergy cost of the electricity generated by the system was determined to be 12.14 USDollar/ GJ and 14.06 US

Dollar/GJ, respectively. The difference between the results was attributed to the differences in the principles and assumptions of the methods. In the SPECO method, a unit cost is appointed to each material in a stream at a given state, while, in the MOPSA method, a unit cost is appointed to each exergy without regard to the state of the stream. For example, in the study, for the analysis of the water stream in the condenser with the SPECO method, the unit cost of the water stream at the entrance was supposed to have a null value for the calculation of the unit cost of the water stream at the exit, while in the case of the MOPSA method, the unit exergy cost of the water stream in the condenser was calculated using the exergy difference between the entrance state and exit state. In the MOPSA method, the flow rates of the water leaving the condenser and the combustion gas leaving the air preheater had greater costs than that of the flow rate determined with the SPECO method; thus, the production cost calculated with the MOPSA method was higher than that with the SPECO method.

The product cost of the system may be reduced by not dividing thermomechanical exergy into its components. However, especially in equipment-based assessments, this strategy doesn’t yield exact detail about the cost structure of the system. Furthermore, this type of analyses has a poorer accuracy in the estimation of the unit specific exergy cost of the electricity producted by system. The SPECO method requires using same number of equations as the number of the system states for every material stream, whereas in the MOPSA method, the number of equations is almost the same as the number of equipment. Hence, the MOPSA method is preferable in the analysis of complex and large thermal systems. In addition, the MOPSA application accurately determines the unit expenses of the system.

The scientific literature includes several studies on the thermoeconomic analysis methods; however, every approach possesses different features and increasing number of different thermoeconomic analysis methods further complicate the discourse. Thus, to reduce the number of methods, future studies should focus on the development of a common thermoeconomic analysis method that includes the advantages offered by the current methods.

Silveira et al. (2002) applied a thermoeconomic analysis method to a cogeneration systemin a college site to determine the feasibility of replacing the gas turbine in the system. The system comprised a gas turbine attached to a waste boiler. The electricity demand of the campus was approx. 9 MW, although it only met about one third of the electricity demand of the campus and generated approx. 1.764 kg/s saturated steam (at 0.861 MPa) from only one fuel source. The thermoeconomic study revealed that, according to the pay-back period, the system containing the gas turbine ‘‘M1T-06’’ procured from Kawasaki Heavy Industries was the best technique, followed by the system containing the gas turbine “M1T-03” procured from Kawasaki Heavy Industries. According to 10-year savings, the best systems were the systems containing the gas turbine ‘‘CCS7’’ procured from Hitachi Zosen and the gas turbine “IM400” procured from Ishikawajima–Harima Heavy Industries, respectively. Instead, according to the exergoeconomic analysis, the best system, in other words the system with the lowest EMC, was the system containing the gas turbine ‘‘ASE50’’ procured from Allied Signal, followed by the system containing the gas turbine‘‘IM400 HI-FLECS’’ procured from Ishikawajima–Harima Heavy Industries. The researchers concluded that the design and operational parameters of the system were of importance in the evaluation of the cogeneration systems and after having overcome the initial complications, the EMC method could prove a good instrument for optimizing of a cogeneration system. Since this method is a direct algebraic method by nature, its advantages include its low computational time, ease of handling, and allowing changes in the parameters when needed.

CHAPTER 3. MATERIALS AND METHOD

3.1. System Description and Assumptions

Before moving on to cogeneration plant analysis, it might be useful to present an extensive introduction of the system components. The power plant is situated at Adana, Turkey and has a capacity of 14.25 MW. The major components of the plant include a boiler (B), an economizer (ECO), a turbine (TE), four ventilation fans (VF), a chimney (CH), and two pumps (P). Figure 3.1 illustrates the representation of the cogeneration system in the plant.

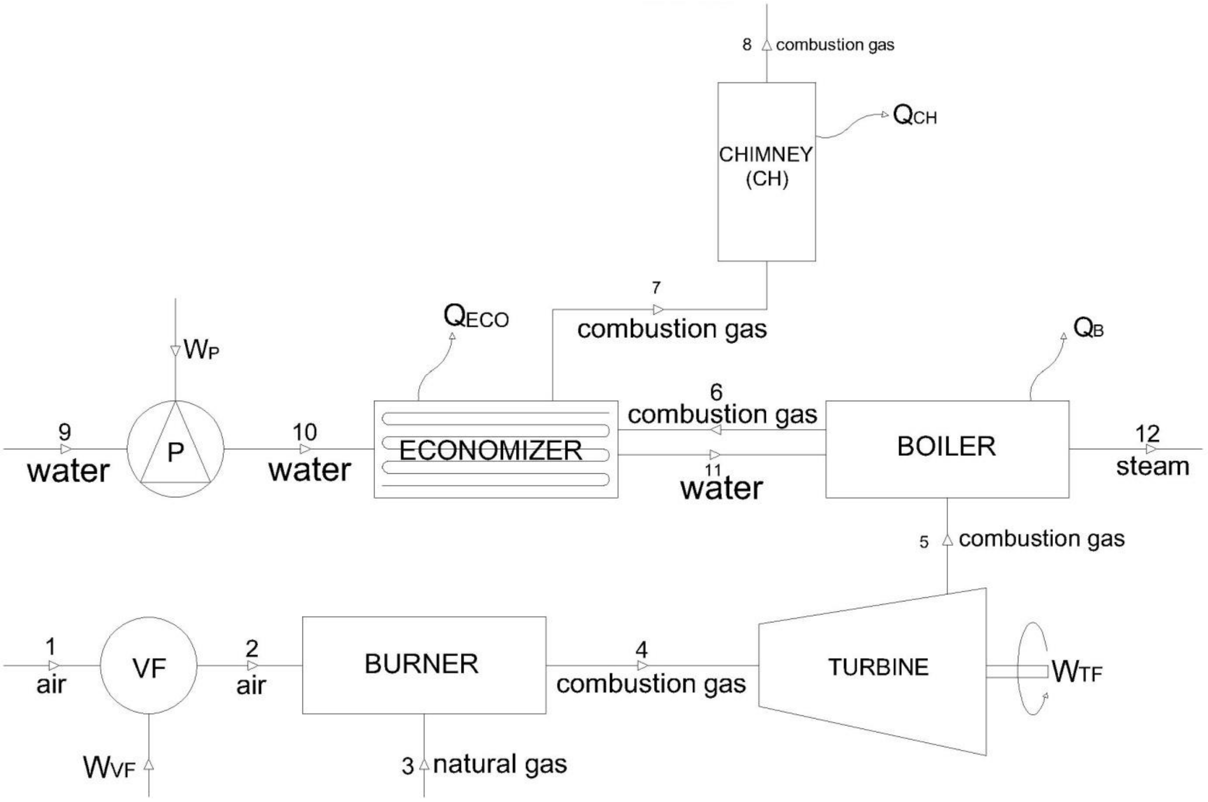

Figure 3.1. Graphic illustration of the power plant

The steam capacity and steam pressure of the boiler are 25 t/h and13 bar, respectively. The four ventilation fans have a total capacity of 46000 m3/h (30 kW) and supply the combustion air to the burner. Natural gas is the fuel of the cogeneration system and its composition is given in Table 3.1. The boiler and economizer have horizontal and vertical heat exchangers. Table 3.2. shows the operating conditions of the cogeneration system. The feed water pump has a capacity of 83 kW (25 t/h) and the steel chimney hasn’t isolation material. First, the feed water is pumped into the economizer and, then, passes through the boiler in which steam generation takes place using the heat exchanger tubes inside the boiler.

Assumptions of this study are:

- *i.* The plant functions in a steady mode.
- *ii.* The idyllic gas principles are accepted for the air and combustion gas.
- *iii.* The pressure losses in the piping system and ducts are ignored.
- *iv.* Kinetic and potential energy are neglected.
- *v.* A classic boiler is utilized in the system.
- *vi.* The physical exergy of the fuel was neglected.
- *vii.* Adiabatic conditions are assumed for the turbine.

Table 3.1. The composition of the natural gas (Ozdil and Pekdur 2016)

Component	Formula	Volume fraction (%)
Methane	CH_4	98.680
Ethane	C_2H_6	0.211
Propane	C_3H_8	0.043
Butane	C_4H_{10}	0.017
Pentane and others	C_5H_{12}	0.035
Carbon dioxide	CO_2	0.035
Oxygen	O_2	0.000
Nitrogen	N_2	0.829
		(kcal/kg)
GCV/HHV		13,459
LHV		12,132

Table 3.2. Operating conditions of the cogeneration system

Mass flow rate (Natural gas)	0.5179 kg/s
Flow rate (Steam)	22 t/h
Steam pressure	12 bar
Steam temperature	190 °C
Flow rate (Combustion gas)	40.21 kg/s
Flow rate (Air)	46,000 m^3/h
Flow rate(Water)	22 t/h

3.2. Analysis

The main principle of the cogeneration system is to generate heat and work utilizing a only one fuel to improve the energy consumption of the system.The study investigates the most and least effective components of the cogeneration system by performing the energy and exergy analyses of the system. According to the first and second law of thermodynamic, the thermodynamic efficacies of the cogeneration system are given as energy and exergy efficiencies. Figure 3.2. shows illustration of the components of cogeneration plant. Using the related thermodynamic tables and EES software, the thermodynamic features of the water, steam, and combustion gases were determined for use in the calculations. The thermodynamic properties of the reference environment were accepted to be T_0 = 25 ^oC and P_0 = 101.3 kPa. The temperature measurement was performed with the TESTO 435 measurement device with a NiCr-Ni, K-type thermocouple in the ranges of -60, +300 ^oC, and 0.5 ^oC sensitivity. The portable TESTO 350 device for combustion gases was employed in the determination of the composition of the combustion gases released by the chimney. Table below shows the mole fractions of the combustion gases.

Table 3.3. Composition of the combustion gas (Ozdil and Pekdur 2016)

Combustion Gas	Mole fraction (%)
NO	11.68
NO_2	17.91
CO	6.36
O_2	15.5
CO_2	48.55

3.2.1. Energy analysis for the system components

Mass and energy equilibration equations for the energy analysis are given by (1) and (2):

Mass Inlet = Mass Outlet $(\Sigma \dot{m}_{in} = \Sigma \dot{m}_{out})$ (1)

Energy Inlet – Energy Outlet = Net Energy $(Q + W = \Sigma \dot{m}_{out}h_{out} - \Sigma \dot{m}_{in}h_{in})$ (2)

a) Energy equilibration equation for the adiabatic turbine is given by (3):

$$E_4 = E_5 + W_{TE} \tag{3}$$

b) Energy equilibration equation for the conventional boiler is given by (4):

$$E_5 + E_{11} = E_{12} + E_l \tag{4}$$

$$E_l = E_{cg} + Q_{loss} \tag{5}$$

$$E_{cg} = \dot{m}_{fuel}\overline{m}_{cg}\overline{C}_{p\text{-}cg}\,(T_{comb} - T_0) \tag{6}$$

E_l, E_{cg}, and Q_{loss} refers to the energy loss, the energy of the combustion gas, and the heat loss through the surface of the boiler via radiation.

A sample calculation can be seen below:

E_{cg} = 0,5179(kg/s) * 1,0092 (kg/s) * 44,3384 (kJ/kmolK) * (533 K-298 K)
E_{cg} = 5446,3059kJ/sn

$E_5 + E_{11} = E_{12} + E_l$
$\dot{m}_5\, h_5 + \dot{m}_{11}\, h_{11} = \dot{m}_{12}\, h_{12} + E_l$
40,2132 * 469,92164 + 6,11 *763 = 6,11 * 2789 + E_l
El = 6518,1993kJ/sn

$E_l = E_{cg} + Q_{loss}$
Q_{loss}= 5446,3059kJ/sn - 6518,1993kJ/sn
Q_{loss}=1071,8935kJ/sn

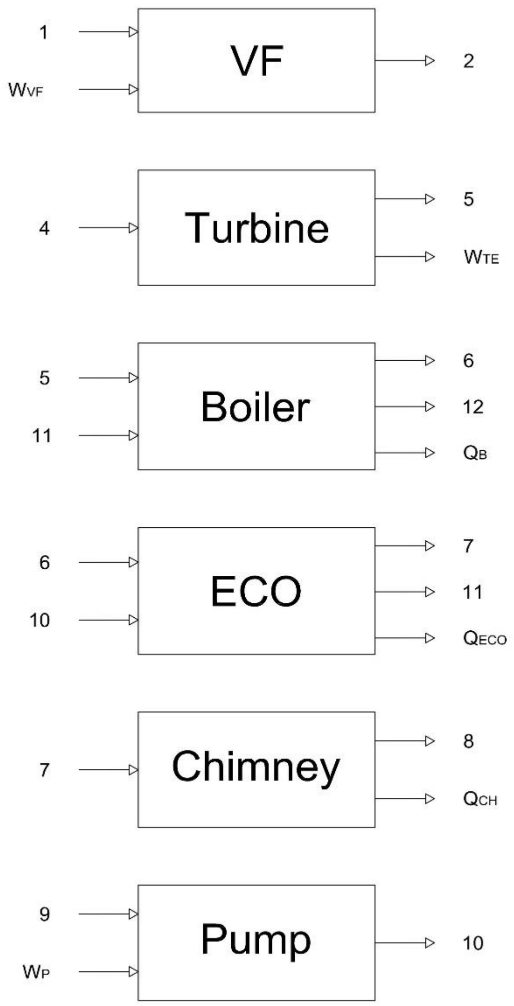

Figure 3.2. Illustration of the cogeneration plant (Ozdil and Pekdur 2016)

c) Energy equilibration of the economiser is given by Eq. (7):

$$\dot{m}_6 h_6 + \dot{m}_{10} h_{10} = \dot{m}_7 h_7 + \dot{m}_{11} h_{11} + Q_{loss} \qquad (7)$$

d) Energy equilibration of the chimney is given by Eq. (8):

$$\dot{m}_7\, h_7 = \dot{m}_8\, h_8 + Q_{CH} \qquad (8)$$

e) Energy equilibration of the pump is given by Eq. (9):

$$\dot{m}_9\, h_9 + W_P = \dot{m}_{10}\, h_{10} + Q_P \qquad (9)$$

f) Energy equilibration of the ventilation fan is given by Eq. (10):

$$\dot{m}_1\, h_1 + \dot{W}_{vf} = \dot{m}_2\, h_2 + Q_{Loss} \qquad (10)$$

3.2.2. Exergy analysis for the system components

General equilibration equations for exergy analysis are given by (11):

$$\text{Exergy Inlet} - \text{Exergy Outlet} - \text{Exergy Destruction} = \text{Net Exergy} \tag{11}$$

A comprehensive exergy analysis of the cogeneration system was performed in order to reflect real-life thermodynamic performance of the system. The exergy analysis of cogeneration systems is performed separately for each component because of complexity of the cogeneration system.

The chemical exergy of the natural gas was found with Eq. (12):

$$ex_{ng}^{ch}= (LHV)^{*}\ \varphi_{dry} \tag{12}$$

where(LHV) and φ represent the lower heating value of the natural gas and the chemical exergy factor, respectively. Using the values given in Table 3.1., the chemical exergy factor of the natural gas is calculated with Eq. (13):

$$\varphi_{dry} = 1.0334+0.0183(h/c)- 0.0694(1/Nc) \tag{13}$$

The general exergy formula to calculate the physical exergy (14):

$$ex^{ph} = (h - h_0) - T_0(s-s_0) \tag{14}$$

The chemical exergy of the combustion gas is calculated with Eq. (15-16):

$$Ex_{cg}= Ex_{cg}^{ph} + Ex_{cg}^{ch} \tag{15}$$

$$Ex_{cg}= \overline{\dot{m}}_{ng}{}^{*}[\ \overline{\dot{m}}_{cg}\{C_{p\text{-}mix}(T_{cg}-T_0)-T_0\ln(T_{cg}/T_0)+RT_0\ln(P_{cg}/P_0)\}+\dot{m}_{cg}{}^{*}ex_{cg}^{ch}] \tag{16}$$

The chemical exergy of the combustion gas (ex_{cg}^{ch}) can be calculated with Eq. (17)

$$ex_{cg}^{ch}= \Sigma\, x_i\, ex_k^{ch} + RT_0\, \Sigma\, x_i \ln x_i \tag{17}$$

$x_i$and ex_k^{ch} represent the volume fraction and chemical exergy of each combustion gas component (Table 3.3), respectively. R and T_0 represent the general gas constant and the ambient temperature, respectively.

With application of the 2nd law of thermodynamic to system:

a) Exergy equilibration equation of the turbine is given by (18):

$$Ex_4 = Ex_5 + W_{TE} + \dot{E}x_D \qquad (18)$$

b) Exergy equilibration equation for the conventional boiler can be obtained as (19):

$$Ex_5 + Ex_{11} = Ex_6 + Ex_{12} + Q_B(1 - T_0/T_S) + \dot{E}x_D \qquad (19)$$

Sample calculation can be seen below:

$$Ex_5 + \dot{m}_{11}\, ex_{11} = Ex_6 + \dot{m}_{12}\, ex_{12} + Q_{loss}(1 – T_0/T_s) + Ex_D$$

$$42201{,}988 + 6{,}11 * 130{,}6844 = 36473{,}211 + 6{,}11 * 846{,}6764 + 1071{,}8935 * (1 - 298/648) + Ex_D$$

Ex_D = 775,111385kJ/sn

c) Exergy equilibration equation for the economizer is given by (20):

$$Ex_6 + Ex_{10} = Ex_7 + Ex_{11} + Q_{ECO}(1 - T_0/T_S) + \dot{E}x_D \qquad (20)$$

d) Exergy equilibration equation for the chimney is given by (21):

$$Ex_7 = Ex_8 + Q_{CH}(1 – T_0/T_s) + Ex_D \qquad (21)$$

e) Exergy equilibration equation for the pump is given by (22):

$$\dot{m}_9\, ex_9 + W_P = \dot{m}_{10}\, ex_{10} + Q_P.(1 – T_0/T_s) + Ex_D \qquad (22)$$

f) Exergy equilibration equation for the ventilation fan is given by (23):

$$\dot{m}_1\, ex_1 + \dot{W}_{vf} = \dot{m}_2\, ex_2 + Q_{Loss}(1 – T_0/T_s) + Ex_D \qquad (23)$$

3.2.3. Energy Efficiencies

Energy efficiencies can be described as the ratio of the energy outlet to the energy inlet and calculated with Eq. (24):

η_I= energy outlet / energy inlet = 1 – (energy loss / energy inlet) (24)

a) Turbine

The energy efficiency of the turbine is calculated using the 1st law of thermodynamic. For this estimation, generated power (electricity) is considered as the energy input while energy difference between the inlet and outlet combustion gases can be accepted to be the energy outlet. The energy efficiency of the turbine can be given by Eq. (25):

$$\eta_{I,TE} = W_{TE} / (\dot{m}_4 h_4 – m_5 h_5) \quad (25)$$

b) The energy efficiency of boiler can be found using Eq. (26):

$$\eta_{I,B} = (\dot{m}_5 h_5 - \dot{m}_6 h_6) / (\dot{m}_{12} h_{12} - \dot{m}_{11} h_{11}) \quad (26)$$

c) The energy efficiencyof economizer can be calculated using Eq. (27):

$$\eta_{I,ECO} = (\dot{m}_{11} h_{11} - \dot{m}_{10} h_{10}) / (\dot{m}_6 h_6 - \dot{m}_7 h_7) \quad (27)$$

d) The energy efficiency of the chimney can be calculated using Eq. (28):

$$\eta_{I,CH} = (\dot{m}_8 h_8) / (\dot{m}_7 h_7) \quad (28)$$

e) The energy efficiency of the pump can be calculated using Eq. (29):

$$\eta_{1,P} = \dot{m}_9 (h_{10} – h_9) / W_P \quad (29)$$

f) The energy efficiency of the ventilation fan can be calculated using Eq. (30):

$$\eta_{1,VF} = \dot{m}_1 (h_1 – h_2) / W_{VF} \quad (30)$$

g) Energy efficiency of the overall system

Energy utilization factor (EUF) is used in the determination of the energy efficiency of cogeneration system and calculated using Eq. (31).

$$\eta_{I,system} = (W + Q)/ \dot{m}_{ng}*LHV \qquad (31)$$

The energy efficiency of the cogeneration system was accepted to be equal to the percentage of the energy provided to the system. W represents the power generation through turbine and Q represents the process heat. With respect to the input of the cogeneration system, it can be described as the supplied fuel energy. The rise in the energy of the feeding water and generated power can be defined as the product of cogeneration system.

3.2.4. Exergy Efficiencies

The energy efficiency analysis is not a promising approach to investigate the system performance due to the equivalence of heat and electricity. Therefore, compared with energy analysis, exergetic efficiency, similarly referred to as the 2nd law efficiency, affords a more accurate evaluation for the system performance. In the determination of the exergy efficiency of the system, the energy quality must be considered.

The exergy efficiency is the ratio of the exergy output to the exergy input. The common exergy efficiency can be defined with Eq. (32):

$$\eta_{II} = \text{exergy output / exergy input} = 1 - (\text{exergy loss / exergy input}) \qquad (32)$$

a) Turbine

The exergy efficiency of the turbine can be found with Equ. (33)

$$\eta_{II,TE} = W_{TE} / (\dot{m}_4 ex_4 - \dot{m}_5 ex_5) \qquad (33)$$

b) Boiler

To find the exergy efficiency of the boiler, the exergy transfer in the boiler through the heat exchangers is accepted to be the exergetic product and the difference between the exergy rate of the combustion gases is accepted to be exergetic fuel. Hence, the exergy efficiency of the boiler is calculated with Equ. (34):

$$\eta_{II,B} = (\dot{m}_{12} ex_{12} - \dot{m}_{11} ex_{11}) / (\dot{m}_5 ex_5 - \dot{m}_6 ex_6) \qquad (34)$$

c) The exergy efficiency of the economiser can be calculated with Eq. (35):

$\eta_{II,ECO}= (\dot{m}_{11}ex_{11} - \dot{m}_{10}ex_{10}) / (\dot{m}_6ex_6 - \dot{m}_7ex_7)$ (35)

d) The exergy efficiency of the chimney can be calculated with Eq. (36):

$\eta_{II,CH} = (\dot{m}_8ex_8) / \dot{m}_7ex_7$ (36)

e) Exergy efficiency for overall system

The exergy efficiency of the cogeneration system is accepted to be equal to percentage of the exergy provided to the system. Hence, the exergetic efficiency can be calculated with Eq. (37)

$\eta_{II,system} = W+E_Q / Ex_{ng}$ (37)

whereEx$_{ng}$ is the chemical exergy of natural gas.

3.2.5. Exergoeconomic Analysis

This study is carried out tomeet and develop the economic point of view for the cogeneration power plant using the actual operation data. The evaluation of exergetic performance for the components of cogeneration system and exergy-cost relations are done to show the relationship between thermodynamics and thermoeconomic evaluation of the cogeneration plants for food industry.The exergoeconomic analysis is done using SPECO method.

Specific Exergy Costing (SPECO) method, which defines the fuel and product of a components getting a regular record of all exergy supplements to and disposals from all the exergy streams of the system, and calculates the costs implementing main rules from business administration. (Lazzaretto and Tsatsaronis, 2006)

In a conventional economics analysis, for each control volume k, a cost equilibration is often derived for the total system operating under steady state conditions:

$$\sum_{in} C_k + Z_k^T = \sum_{out} C_k + C_k^W + C_k^Q \quad (38)$$

$$C_k = c_k Ex_k \quad (39)$$

$$C_k^w = c_k W_k \quad (40)$$

$$C_k^Q = c_k E_k^Q \tag{41}$$

$$Z_k^T = Z_k^{Cl} + Z_k^{OM} \tag{42}$$

where C_k, C_k^w, and C_k^Q represent the exergy costs of the streams, power, and heat, respectively; c represents the unit exergy costs of the streams, power, and heat; Ex_k, W_k, E_k^Q represent the exergy of the stream, power, heat ingoing and outgoing the control volume; Z_k^{Cl}, Z_k^{OM} and Z_k^T represent the leveled expenses for the capital investing by hours, operation and maintenance, and the over-all cost of the material within the control volume .

The hourly leveled cost method was employed to find Z_k^{Cl}.

The capital recovery factor (CRF):

$$CRF = \frac{i(i+1)^n}{i(i+1)^n - 1} \tag{43}$$

The cost rate of the sub-systems, CR_k:

$$CR_k = \frac{PEC_k}{\Sigma_{SYSTEM} PEC} \tag{44}$$

The hourly leveled capital investment cost of the kth component, Z_k^{Cl} :

$$Z_k^{Cl} = Z_{SYSTEM}^{Cl} CR_k \tag{45}$$

here, τ, i, j, n, and PEC represent the sum quantity of operating hours of the system under full load conditions, the interest rate, the recovery value ratio, the life time for the system, and the cost of equipment purchase. For the system, τ, i, j, and n were determined as 8200, 0.15, 0.12, and 15 years.

$$Z_k^{OM} = Z_k^{OCl} \phi \tag{46}$$

where the maintenance and operating costs are kept in view by taking the factor ϕ as 0.85 for the cogeneration power plant and its components:

Unit exergy cost of the fuel c_3^{ng},

$$c_3^{ng} = \frac{Pr^{ng}}{ERLHV10^{-6}(\frac{Gj}{kJ})} \tag{47}$$

where $\mathrm{Pr^{ng}}$, LHV, and ER represent the selling value of the fuel in Turkish currency (₺), LHV of the natural gas, and exchange rate between ₺ and USD dollar.

The unit exergy cost of the electricity $\mathrm{c_{21}^{W}} = \mathrm{c_{22}^{W}} = \mathrm{c_{23}^{W}}$,

$$\mathrm{c^{W}} = \frac{\mathrm{Pr^{W}}}{\mathrm{ER3600}(\frac{\mathrm{s}}{\mathrm{h}})10^{-6}(\frac{\mathrm{Gj}}{\mathrm{kJ}})} \tag{48}$$

here, $\mathrm{Pr^{W}}$ and ER represent the selling price of electricity in ₺and the exchange rate between ₺ and USD, respectively.

$C_{D,k}$ represents the expense rate of the exergy destruction and revealed how many dollars per an hour (US Dollar/h) are destructed during the process of the unit and given by Eq. (49):

$$C_{D,k} = c_{F,k}Ex_{D,k} \tag{49}$$

The origins of the cost of a component can be divided into two groups: 1) non-exergy related costs (capital investments, operating and maintenance expenses) and 2) exergy destructıon and exergy loss. Exergoeconomic factor, f_k, can be used in evaluation of the performance of a component to derive information about the related significance of each group and is defined by Eq. (50):

$$\mathrm{f_k} = \frac{\mathrm{Z_k^T}}{\mathrm{Z_k^T} + \mathrm{c_{F,k}}(\mathrm{Ex_{D,k}} + \mathrm{Ex_{L,k}})} \tag{50}$$

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Thermodynamic Analysis Findings

In the study, the thermodynamic analysis of a cogeneration system was done using the 1st and 2nd law of thermodynamic to find the efficiency of the system. Furthermore, the influence of steam pressure on energy and exergy efficiencies of the boiler was investigated. Table 4.1. shows the fluid types, temperatures, pressures, mass flow rates, and exergy rates for the cogeneration plant in terms of their state numbers.

Table 4.1. The exergy rate and other properties (for state no, please refer to Figure 3.1) (Ozdil and Pekdur 2016)

State no	Fluid Type	Mass flow rate (kg/s)	Temperature (K)	Pressure (kPa)	$\dot{E}x$ (kW)
1	Air	15.486	303	101.325	9.933
2	Air	15.486	295	101.325	0.135
3	Natural gas	0.518	288	2600	2,723,282.626
4	Comb. gas	40.213	1033	1700	49,524.458
5	Comb. gas	40.213	763	1700	42,201.988
6	Comb. gas	40.213	533	1700	36,473.211
7	Comb. gas	40.213	459	1700	34,793.617
8	Comb. gas	40.213	403	1700	33,596.101
9	Water	6.11	377	1900	238.952
10	Water	6.11	378	1900	245.196
11	Water	6.11	453	1900	798.481
12	Steam	6.11	463	1200	5173.192
Boiler	Ex_{LOSS}	-	-	-	578.954
ECO	Ex_{LOSS}	-	-	-	404.105
CH	Ex_{LOSS}	-	-	-	669.204

Figure 4.1., 4.2., 4.3., and 4.4. demonstrate the exergy destruction, energy and exergy efficacies of the main units, and distribution of exergy destruction, respectively. Table 4.2. shows the exergy destructions and energy and exergy efficiencies computed with the above equations. As given the table, the energy efficiencies of the CH, ECO, and boiler are approximately 63.99%, 66.03%, and 79.91%, respectively, while the exergy efficiencies of the CH, ECO, and boiler are 96.55%, 32.94%, and 76.36%, respectively. As revealed by Figure 4.2., the energy efficiencies of the majority of the components are above 0.6. The major sources of the inefficiency in the system are listed below.

i. The value of the excessive air supply to system significantly affected the efficiency of the system. The mass flowing rate of the combustion gas increased with raising amounts of excess air. The increase in the mass flow rate of the combustion leads to decreased component temperatures and increased heat loss in system, hence, the efficiency of system declines.

ii. Chemical reaction in the combustion procedure can lead to rise in the system irreversibility. The results obtained in the study indicated that, although there is an opportunity for improvement through the reduction of the level of excess air, the cogeneration system had satisfactory combustion efficiency when the composition of the combustion gas obtained from the chimney is considered.

iii. The highest irreversibility was determined in the boiler, which was attributed to the low level of heat transfer from the combustion gas to water by means of heat exchangers. The steam is among the system outputs and its pressure and temperature affect the boiler performance significantly. Thus, increasing the pressure and temperature of the steam may prove beneficial in increasing the heat transfer to the water, which, in turn, will increase the powers of the boiler output and overall system output. The system performance can be optimized and enhanced by increasing heat transfer to water, which results in the effective arrangement of the heat exchangers both in the boiler and ECO and help select better materials. The ECO had the second highest irreversibility after the boiler. The irreversibility of the boiler can be reduced by reducing the temperature of the combustion gas obtained from turbine. The temperature of the boiler output declines with decreasing combustion gas temperature and thus, the irreversibility of the ECO is reduced. A better insulation can also contribute to the decrease in the irreversibility of the ECO.

iv. The fuel type is also of importance in the efficiency of the overall system, since the calorie finding representing internal energy of fuel directly affects the efficiency of the system.

Table 4.2. The exergy destruction and energy and exergy efficiency values of components in the cogeneration system (Ozdil and Pekdur 2016)

Components	$\dot{E}x_D$(kW)	η_I(%)	η_{II}(%)
Boiler	775.11	79.91	76.36
ECO	722.20	66.03	32.94
CH	528.31	63.99	96.55
Turbine	0	100	58.58
Pump	64.80	31.65	7.52
Ventilation Fan	39.28	24.10	32.66

The steam pressure was increased by 1 bar until it reached 13 bar from 6 bar to investigate how the efficiency of the system is affected by steam pressure. Given in Figure 4.5., as the steam pressure increases, the internal energy of the steam goes up so that the power output increases. When the steam pressure is increased from 6 bar to 13 bar as shown in Table. 4.3,

i. 1.5% rise in the energy efficiency of the boiler was obtained.
ii. 9.25% rise in the exergy efficiency of the boilerwas obtained.

Hence, conclusively, increasing the steam pressure at boiler output positively affected efficiencies of boiler and system.

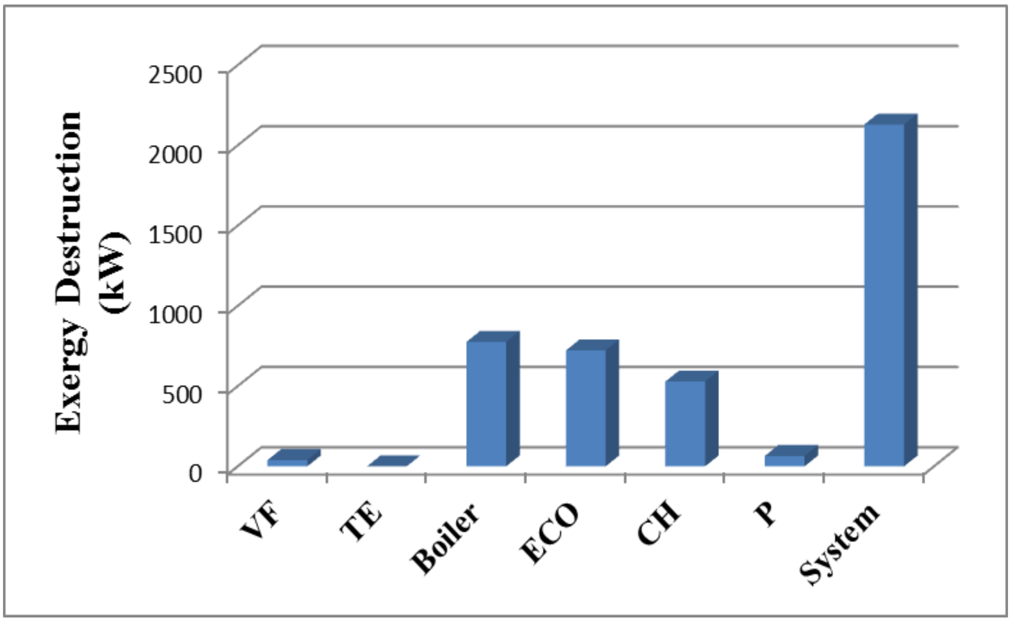

Figure 4.1. Exergy destruction in the components of the cogeneration system (Ozdil and Pekdur 2016)

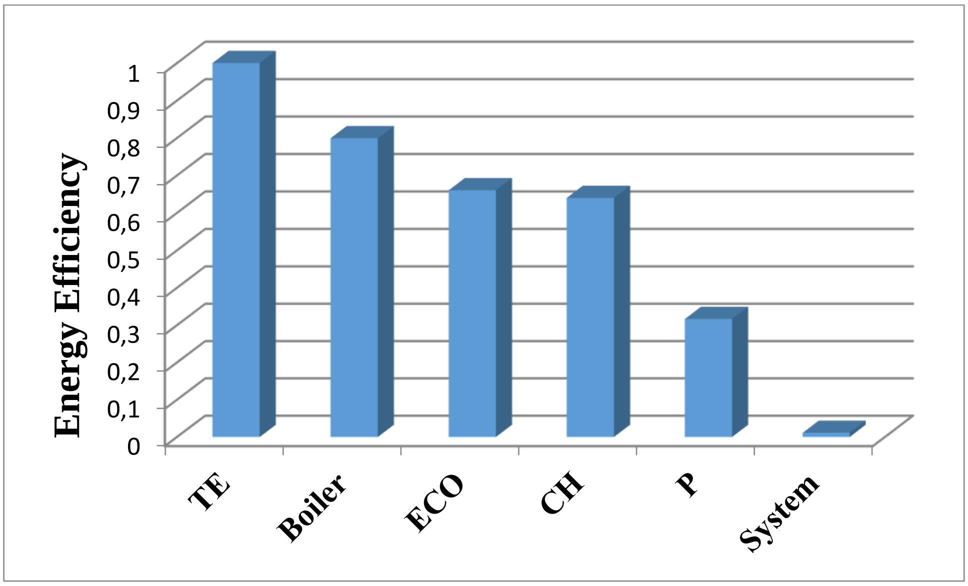

Figure 4.2. Energy efficiency of the main components of the cogeneration system (Ozdil and Pekdur 2016)

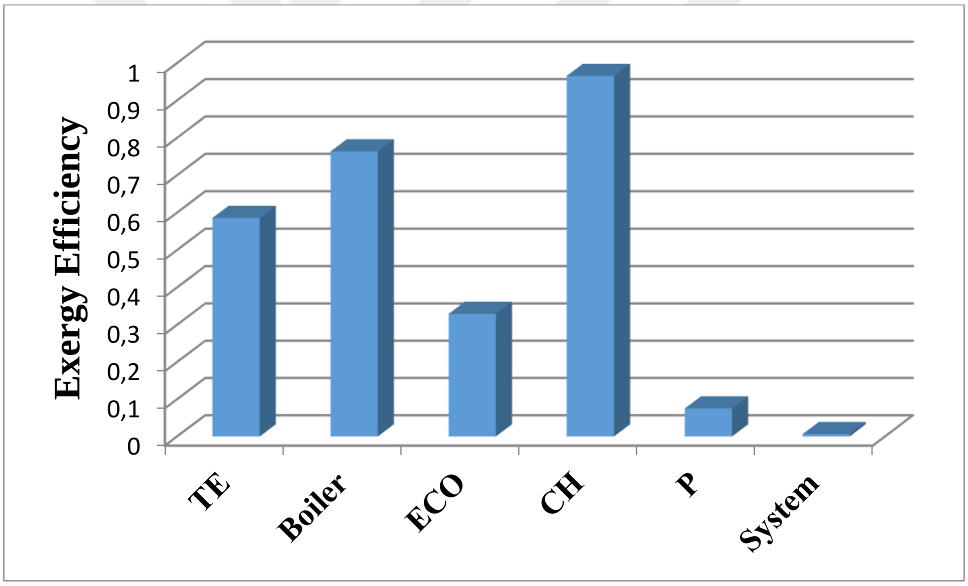

Figure 4.3. Exergy efficiency of the main components of the cogeneration system (Ozdil and Pekdur 2016)

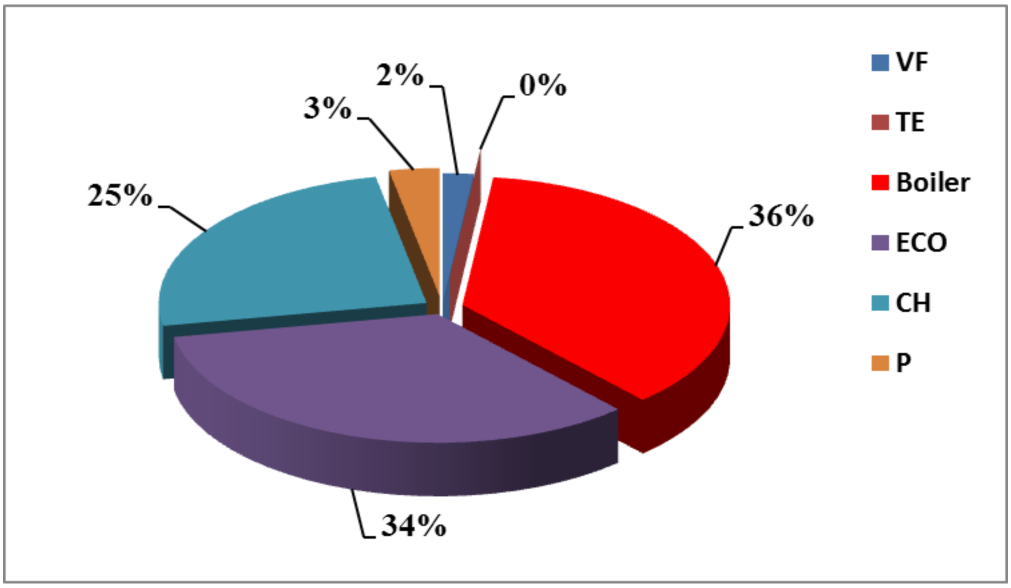

Figure 4.4. Distribution of the exergy destruction rates of the components of the cogeneration system (Ozdil and Pekdur 2016)

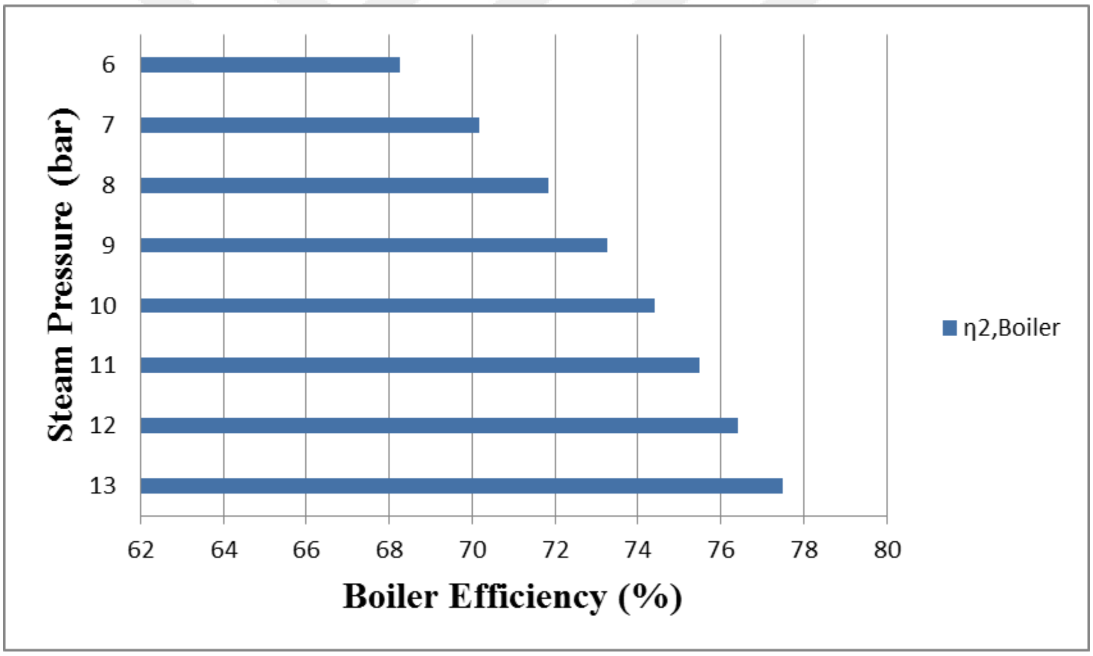

Figure 4.5. The impact of steam pressure on the exergy efficiency of the boiler (Ozdil and Pekdur 2016)

Table 4.3. The impact of the steam pressure on the energy and exergy efficiency of boiler at 6 bar and 13 bar (Ozdil and Pekdur 2016)

	Pressure (bar)		Total
	6	13	Changes (%)
$\eta_{I\ (\%)}$	78.41	79.91	1.5
$\eta_{II\ (\%)}$	68.25	77.50	9.5

4.2. Exergoeconomic Analysis Results

The investigation of exergoeconomic performance is put forth to Show the relationship between thermodynamics and economic evaluation with respect to the use of thermodynamic laws and exergoeconomic equations. Table 4.4 shows the total costs, purchased equipment costs, hourly leveled capital investing costs, and operating and maintenance costs of equipment and overall system. Figures 4.6., 4.7., and 4.8 shows the cost rates, purchased equipment costs, and total investment costs of the equipment, respectively. As revealed by the figures, the CPP equipment had the highest value. Table 4.5. shows the unit exergy cost and exergy expenses of equipment in CPP.

Given in Table 4.5., the unit exergy expense and exergy expense of the fuel were 0.05 US Dollar/GJ and 490.23US Dollar/h. According to results given in Table 4.4, the operation and maintenance cost, capital investment cost, and total cost of the system were found as 231.66, 218.55, and 450.21 US dollar/hour.

Table 4.4. The distribution of the cost rate, cost of the bought equipment, the leveled capital investing, the costs of operation and maintenance, and total expenses by material (Ozdil and Pekdur 2016)

COMPONENTS	CR_k	PEC[US Dollar]	Z_k^{CI}[US Dollar/h]	Z_k^{OM} [US Dollar/h]	Z_k^{T}[US Dollar/h]
Ventilating Fan (VF)	0.03	236.207	7.54	7.99	15.52
Turbine	0.23	1.574.713	50.24	53.26	103.50
Boiler	0.46	3.149.425	100.48	106.51	206.99
Economizer (ECO)	0.16	1.102.299	35.17	37.28	72.45
Chimney (CH)	0.08	551.149	17.58	18.64	36.22
Pump (P)	0.03	236.207	7.54	7.99	15.52
TOTAL	1.00	6.850.000	218.55	231.66	450.21

Table 4.5. The distribution of the rate of exergy, cost of unit exergy and cost of exergy (Ozdil and Pekdur 2016)

State No.	Ex [GJ/hour]	c [US Dollar/GJ]	C [US Dollar/hour]
1	0.04	0.00	0.00
2	0.00	39028.17	19.02
3	9803.82	0.05	490.23
4	178.29		509.25
5	151.93	0.05	7.60
6	131.30	0.05	6.57
7	125.26	0.05	6.26
8	120.95	0.35	42.39
9	0.86	0.00	0.00
10	0.88	24.11	21.29
11	2.87	32.67	93.91
12	18.62	16.20	301.79
VF - 13	0.14	24.69	3.49
Turb. - 14	0.37	1618.51	605.15
Boiler - 15	2.79	0.05	0.14
ECO - 16	2.60	0.05	0.13
CH - 17	1.90	0.05	0.10
Pump - 18	0.23	24.69	5.76

In figure 4.9, cost rates of exergydestruction for whole equipment are demonstrated whilst the uttermost cost rate of exergydestruction is obtained in CPP equipment. The factors of exergoeconomic for whole equipment are exhibited in figure 4.10. The most important reason of the highest exergoeconomic factor in the pump is that the initial investment cost and exergy destruction at it is too low compared to other equipment. But, because of considerably upper value of exergy destruction, lowest exergoeconomic factor is obtained in CPP.

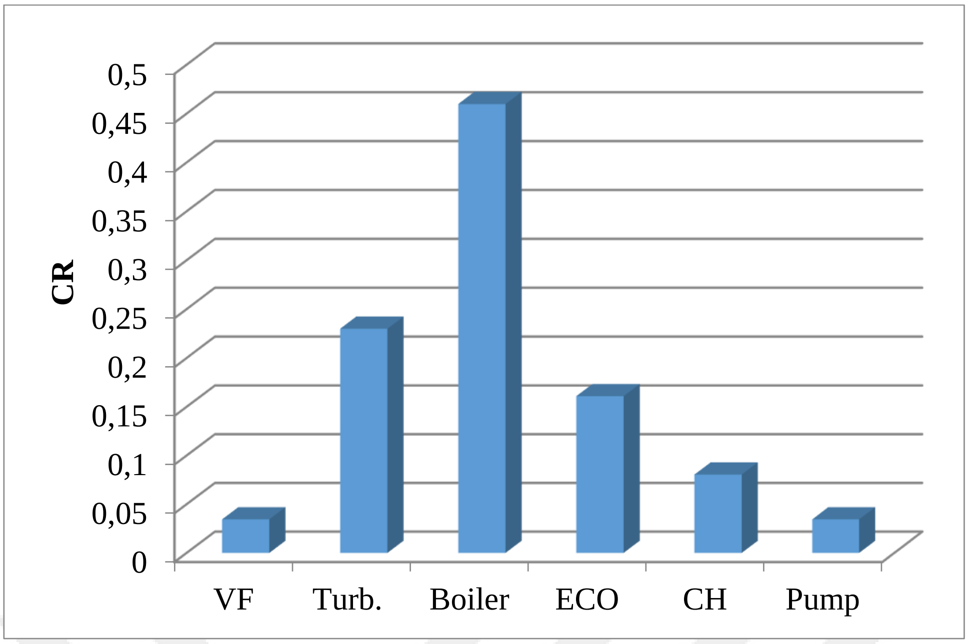

Figure 4.6. The costs of the components of the CPP

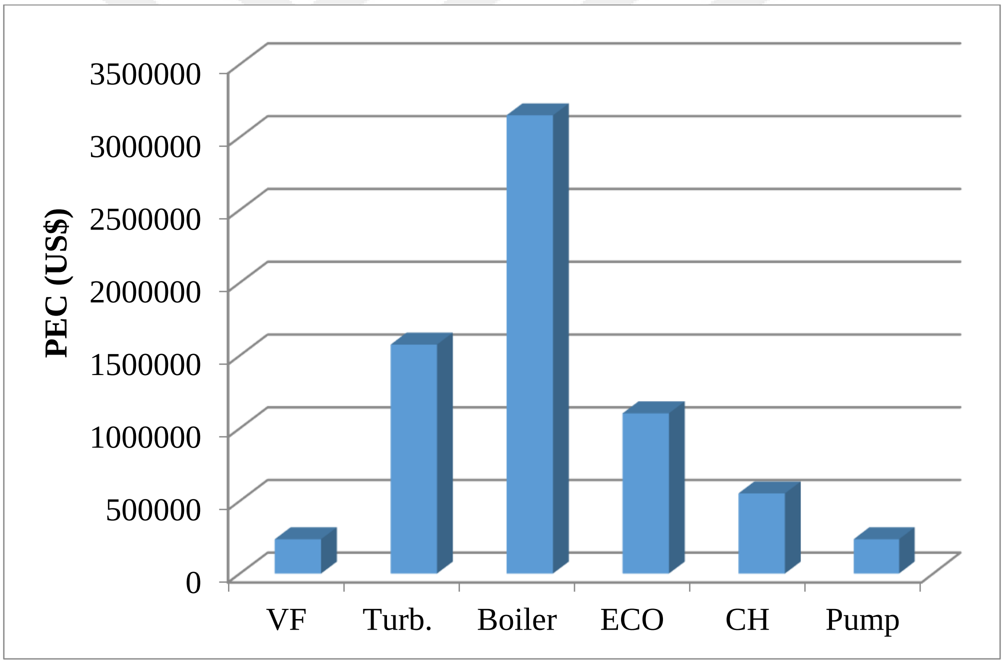

Figure 4.7. The costs of thepurchased equipment for the components of the CPP

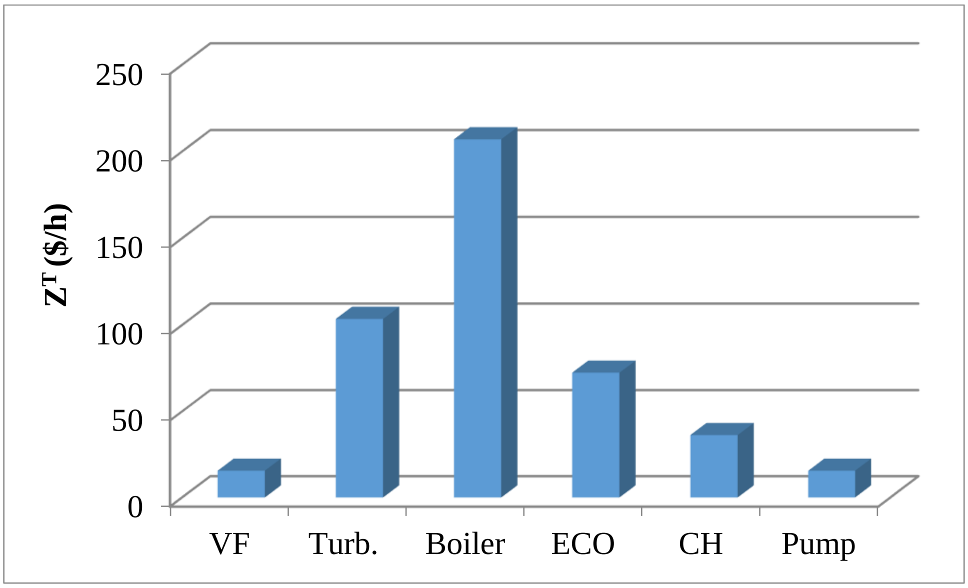

Figure. 4.8. Total investment costs of the components of the CPP

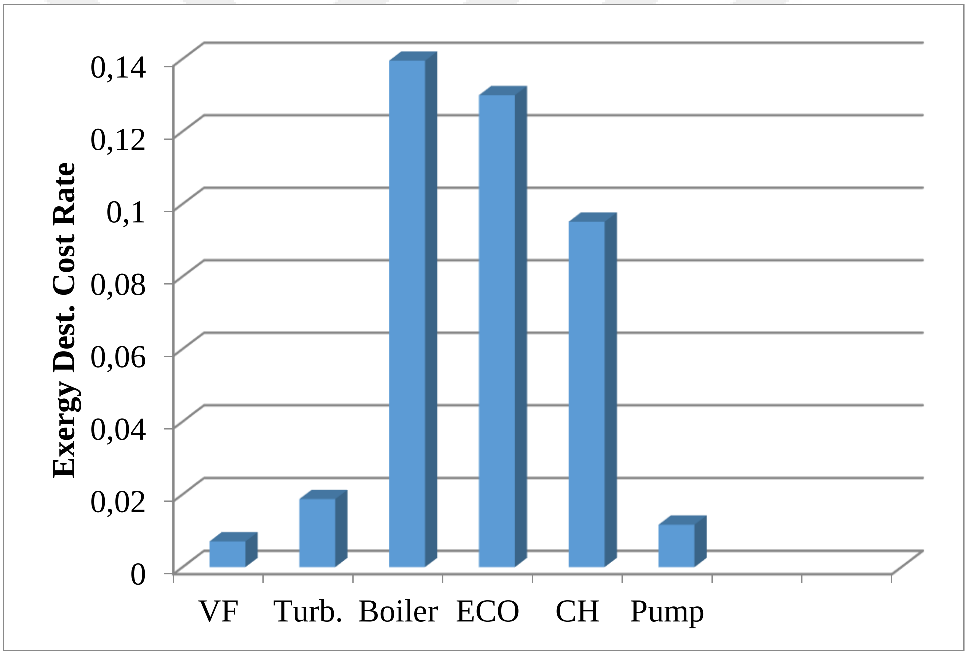

Figure. 4.9. Exergy destruction expense rates of components of the CPP

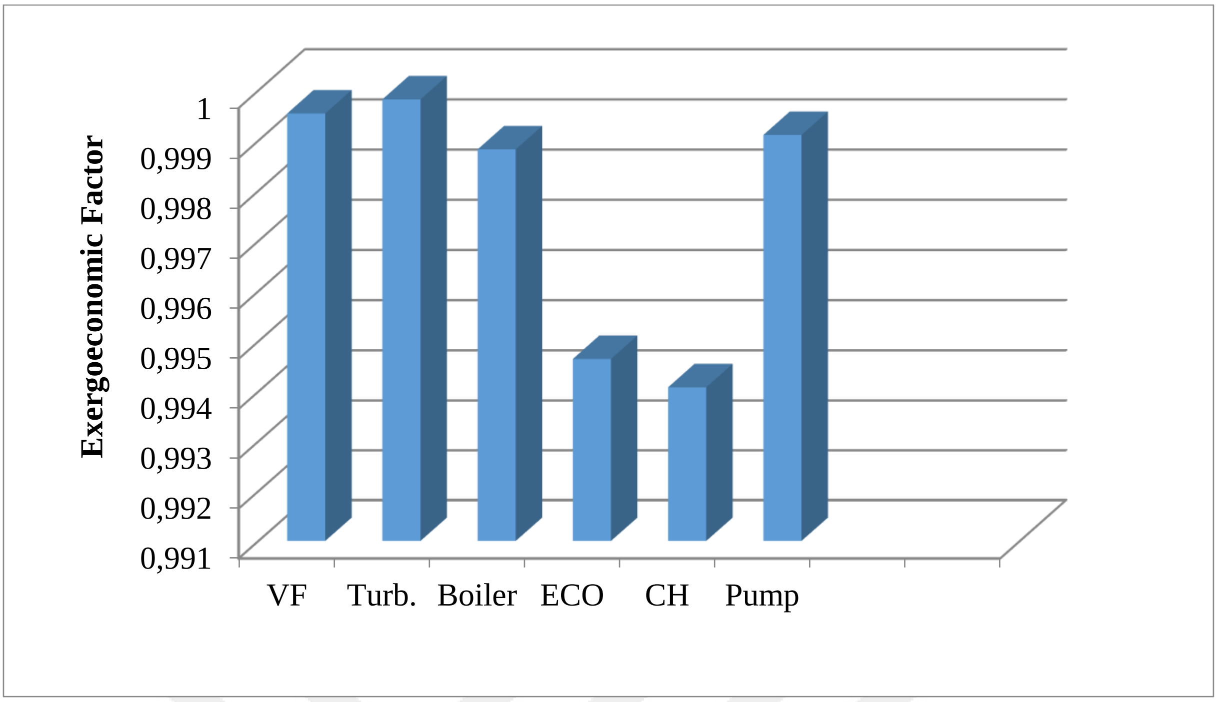

Figure 4.10. Exergoeconomic factors of the components of the CPP

CHAPTER 5: CONCLUSION

In the study, the 1st and 2nd laws of thermodynamic were applied to an actual cogeneration power plant and the energy and exergy analyses were carried out. The findings showed that greatest exergy destruction was around 775.111 kW and had occurred in the boiler, which was attributed to the large value of excessive air directly affecting the combustion gas flow rate. The heat losses in the boiler increase with increasing amounts of excess air due to the decreasing boiler temperature. Furthermore, the steam pressure is a further important parameter for the system efficiency as it stimulates the exergy output positively. Increasing steam pressure, for instance, has positive influence on the system efficiency.

We can list the recommendation to improve the system performance as below:

i. The quantity of the supplied excess air to the system has significant effect on the system efficiency. The increase in the excess air leads to increase of the mass flow rate of the combustion gas. Due to the increase in the mass flow rate of the combustion gas, the boiler temperature decreases and the heat losses in the system increase; after that, the efficiency of the system decreases.

ii. The chemical reaction in the combustion process can give rise to the larger system irreversibility. In this study, composition of the combustion gas gained from the chimney points that the cogeneration system has satisfactory combustion efficiency, but it can be developed in decrement of the excess air amount.

iii. The boiler has the largest irreversibility owing to the poor heat transfer from the combustion gas to the water via the heat exchangers. One of the system outlets is the steam and its pressure and temperature are influential factors on the boiler efficiency. Increasing the steam pressure and temperature results in higher heat transfer to the water, so that the power of the boiler output and overall system output increases.

iv. The system performance can be optimized and developed by increasing the heat transfer to the water which results in effective arrangement of the heat exchanger located in both the boiler and ECO and also better material selection. ECO has the second biggest irreversibility thereafter the boiler. What is more, the irreversibility of the boiler can be diminished by decreasing the temperature of the combustion gas obtained from the turbine. By virtue of the decline in the temperature of the combustion gas, the temperature at the boiler outlet also diminishes and in this manner, irreversibility of the ECO dwindles. The irreversibility of the ECO can also be diminished with effective insulation.

v. The type of the fuel is a further important factor for the efficiency of the overall system as the calorific value representing internal energy of the fuel affects directly the system efficiency.

vi. All of the exergoeconomic factors, belonging the components of the system, are obtained higher than 0.99. When we consider the exergoeconomic factor, which is an important parameter for exergoeconomic analysis, it has been observed that in general all equipment have high values. High exergoeconomic factor results refer to that all monetary costs of the system are happened due to investment cost, operational and maintenance costs. For this reason, trying to increase the exergoeconomic effectiveness of the system will not be very realistic. Because increment of the system efficiency will not affect the monetary costs of the system. If the obtained exergoeconomic factor value is low, the system efficiency can be improved.

REFERENCES

Anonymous. 2017. http://www.megenergy.com/operations/cogeneration Access Date: 26.02.2018

Anonymous. 2017. http://emhk.itu.edu.tr/yuksek-verim-ve-temiz-enerji-kojenerasyon-sistemleri/ Access Date: 26.02.2018

Anonymous. 2010. https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/cogeneration-plant-chp-combined-heat-and-power Access Date: 26.02.2018

Anonymous. 2017. http://www.enerji.gov.tr/tr-TR/Sayfalar/Elektrik Access Date: 26.02.2018

Abusoglu A, Kanoglu M. 2009. Exergetic and thermoeconomic analyses of diesel engine powered cogeneration: Part 1 – Formulations. Applied Thermal Engineering, 29: 234–241.

Bade, MH, Bandyopadhyay S. 2015. Analysis of gas turbine integrated cogeneration plant: Process integration approach. Applied Thermal Engineering 78: 118-128.

Bonnet S, Alaphilippe M, Stouffs P. 2005. Energy, exergy and cost analysis of a micro-cogeneration system based on an Ericsson engine. International Journal of Thermal Sciences, 44: 1161–1168.

Can OF, Celik N, Dagtekin I. 2009. Energetic–exergetic-economic analyses of a cogeneration thermic power plant in Turkey. International Communications in Heat and Mass Transfer, 36: 1044–1049.

Gholamian E, Mahmoudi SMS, Zare V. 2016. Proposal, exergy analysis and optimization of a new biomass-based cogeneration system. Applied Thermal Engineering, 93: 223–235.

Gurturk M, Oztop HF. 2010. Exergy analysis of a circulating fluidized bed boiler cogeneration power plant. Energy Conversion and Management, 120: 346–357.

Kamate SC, Gangavati PB. 2010. Exergy analysis of cogeneration power plants in sugar industries. Applied Thermal Engineering, 29: 1187–1194.

Kim SM, Oh SD, Kwon YH, Kwak HY 1998. Exergoeconomıc Analysıs Of Thermal Systems. Energy, Vol. 23, No. 5, pp. 393–406.

Kumar R. 2017. A critical review on energy, exergy, exergoeconomic and economic (4-E) analysis of thermal power plants. Engineering Science and Technology, an International Journal, 20: 283–292.

Lazzaretto A, Tsatsaronis G. 2006. SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems, Energy, 31(8): 1257-1289.

Lee JH, Kim TS, Kim E 2017. Prediction of power generation capacity of a gas turbine combined cycle cogeneration plant. Energy, 124: 187e197

Mert MS, Dilmaç ÖF, Özkan S, Karaca F, Bolat E. 2012. Exergoeconomic analysis of a cogeneration plant in an iron and steel factory. Energy, 46: 78e84

Nemati A, Nami H, Ranjbar F, Yari M. 2017. A comparative thermodynamic analysis of ORC and Kalina cycles for waste heat recovery: A case study for CGAM cogeneration system. Case Studies in Thermal Engineering, 9 : 1–13.

Orhan MF, Dincer I, Rosen MA. 2009. Energy and exergy analyses of the fluidized bed of a copper–chlorine cycle for nuclear-based hydrogen production via thermochemical water decomposition. Chemical Engineering Research and Design, 87: 684–694.

Ozdemir K, Hepbasli A, Eskin N. 2010. Exergoeconomic analysis of a fluidized-bed coal combustor (FBCC) steam powerplant. Applied Thermal Engineering, 30: 1621-1631.

Ozdil NFT, Tantekin A. 2016. Exergy and exergoeconomic assessments of an electricity production system in a running wastewater treatment plant. Renewable Energy, 97: 390-398.

Ozdil NFT, Pekdur A. 2016. Energy and exergy assessment of a cogeneration system in food industry: a case study. International Journal of Exergy, Vol. 20, No. 2, pp. 254-268

Ozdil NFT, Tantekin A. 2017. Exergoeconomic analysis of a fluidized bed coal combustion steam power plant. Thermal Scıence, Vol. 21, No. 5, pp. 1975-1984.

Puadian N, Li J, Pang S. 2014. Analysis of Operation Parameters in a Dual Fluidized Bed Biomass Gasifier Integrated with a Biomass Rotary Dryer: Development and Application of a System Model. Energies, 7: 4342-4363; doi:10.3390/en7074342.

Santos AC, Puch GZ, Diez DB, Dieguez CG. 2016. Thermodynamic and exergoeconomic analysis of energy recovery system of biogas from a wastewater treatment plant and use in a Stirling engine. Renewable Energy, 88: 171-184.

Silveira JL, Beyene A, Leal EM, Santana JA, Okada D. 2002. Thermoeconomic analysis of a cogeneration system of a university campus. Applied Thermal Engineering, 22: 1471–1483

Uysal C, Kurt H, Kwak HY. 2017. Exergetic and thermoeconomic analyses of a coal-fired power plant. International Journal of Thermal Sciences, 117: 106-120

Wu Y, Yang W, Blasiak W. 2014. Energy and Exergy Analysis of High Temperature Agent Gasification of Biomass. Energies, 7: 2107-2122; doi:10.3390/en7042107.

Yildirim U, Gungor A. 2012. An application of exergoeconomic analysis for a CHP system. Electrical Power and Energy Systems, 42: 250–256.

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Approval of the Graduate School of Natural and Applied Sciences

Director

Assoc. Prof. Dr. Osman Sivrikaya

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Chairman of the Department

İmge

Asst. Prof. Dr. Hatice İmge BAŞEĞMEZ

This is to certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ENERGY, EXERGY AND EXERGOECONOMIC ASSESSMENT OF A COGENERATION SYSTEM IN FOOD INDUSTRY

PEKDUR, Arzu
Master of Science, Department of Nanotechnology and Engineering Sciences
Supervisor: Assoc. Prof. Dr. N. Filiz ÖZDİL
June 2018, 58 pages

ABSTRACT

The study carries out a comprehensive analysis of the first and second law of thermodynamic through their application to 14.25 - MW cogeneration system at the city of Adana, in Turkey. The cogeneration structure comprised a turbine, a boiler, an economizer, a ventilation fan, a pair of pumps, and a chimney. Although the energy requirement for customer was established to be around 10.5 MW, the cogeneration system exceeded the amount requested by the customer and generated roughly 1.35-fold of the originally requested energy. The way the energy and exergy efficiency values are influenced by the members of the system and the functions of the components were analyzed separately to obtain information about the performance of every component individually. The findings showed that boiler had the highest irreversibility with an irreversibility value equaling to 36% of the irreversibility of the entire system, which is attributable to the structure of a boiler. In addition, with a 34% and 25% contribution to the irreversibility of the entire system, respectively, the irreversibility values of the economizer and chimney were notably high. In addition, the study focused on the relations between the steam pressure at the boiler output and energy and exergy efficiency. The investigation of hereby relationship revealed that exergy destruction of the boiler decreased with increasing steam pressure at the boiler output, which leads to increased boiler efficiency. Furthermore, the results showed that combustion efficiencies of the cogeneration structure reached satisfactory levels due to the high molar fraction of the CO_2 at the chimney output.

Keywords: Energy, Exergy, Thermodynamic analysis, Exergoeconomic, Cogeneration systems.

GIDA ENDÜSTRİSİNDE KOJENERASYON SİSTEMİNİN ENERJİ, EKSERJİ VE EKSERJİEKONOMİK DEĞERLENDİRMESİ

PEKDUR, Arzu

Yüksek Lisans, Nanoteknoloji ve Mühendislik Bilimleri Anabilimdalı

Tez Yöneticisi: Doç Dr. N. Filiz ÖZDİL

Haziran 2018, 58 Sayfa

ÖZET

Bu araştırmada, Adana'da bulunan 14.25 MW kojenerasyon sistemine uygulanan birinci ve ikinci termodinamik kanunların kapsamlı analizi yapılmıştır. Kabul edilen kojenerasyon sistemi türbin, kazan, ekonomizer, havalandırma fanı, iki pompa ve bir bacadan oluşmaktadır. Fabrikanın kendi enerji ihtiyacı yaklaşık 10.5 MW iken kojenerasyon sisteminde ihtiyacın neredeyse 1.35 katı üretilmektedir. Enerji ve ekserji verimliliği üzerine her bir sistem unsurunun görevi ve etkisi, her bileşenin tekil performansı hakkında bilgi edinmek için analiz yapılmıştır. Çalışma sonuçları, maksimum tersinmezliğin kazanda gerçekleştiğini ve bunun da sistemin tamamının tersinmezliğinin % 36'sı olduğunu ve bu tersinmezliğin sadece kazanın doğasından kaynaklandığını belirtmek için önemlidir. Buna ek olarak, ekonomizer ve baca, sırasıyla,% 34 ve% 25 olan daha belirgin tersinmezliğe sahiptir. Bu tezde kazanın çıkışındaki buhar basıncı ile enerji ve ekserji verimi arasındaki ilişki de araştırılmıştır. Kazan çıkışındaki buhar basıncı yükseldiğinde, kazanın ekserji tahribatının azaldığı vurgulanmaktadır; bu sebeple kazanın verimliliği artmektadır. Buna ek olarak, bu kojenerasyon sisteminde baca çıkışında yüksek molar fraksiyon değeri bulunduğu için tatmin edici bir yanma verimi olduğu ortaya çıkmaktadır.

Anahtar Kelimeler: Enerji, Ekserji, Termodinamik analiz, Ekserjiekonomik, Kojenerasyon sistemleri.

ACKNOWLEDGEMENTS

Firstly and above all, I’d like to present my thanks to my supervisor Assoc. Prof. N. Filiz ÖZDİL regarding worthful pathbreaking & encouragement. Furthermore, she also gives me a source of inspiration to study this thesis, the ambition to motivate me greatly contributed to my thesis.

In addition, I would like to thank to my Research Assistant friend Atakan TANTEKİN at Adana Science and Technology University for his friendship and moral support.

Finally, I am greatly indebted to my mother Mesrure GÜRGEN, my aunt Berrin DEMİRALAY who interested my baby when I was at school. I also thank to my beautiful daughters, Eylül and Deniz whom I did not care enough during my studies. And special thanks for my lovely husband Hikmet PEKDUR for his encouragement and support.

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NUMENCLATURE

$\bar{C}_p$	specific heat capacity (kJ/kmolK) Cp
$\dot{\bar{m}}$	molar flow rate (kmol/s)
E	energy rate (kJ/sn)
ex	specific exergy (kJ/kg)
$\dot{E}x_D$	Exergy Destruction (kW)
h	specific entalpy (kJ/kg)
LHV	lower heating value of coal (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
$\dot{Q}$	rate of heat transfer (W)
s	specific entropy (kJ/kg K)
T	temperature (K)
$\dot{W}$	rate of work (W)

Subscripts

AF	aspiration fan
CH	chimney
cg	combustion gas
destr.	destruction
ECO	economizer
ng	natural gas
P	Pump
TE	Turbine
VF	Ventilation fan
0	reference state

Greek symbols

η_{I}	first law efficiency
η_{II}	second law efficiency

CHAPTER 1. INTRODUCTION

Energy is critically noteworthy issue throughout the world coupled with the reduction of fossil fuel and environment pollution. Fossil fuels are currently the leading energy source worldwide, albeit the finite fossil fuel resources. This poses the threat of energy poverty. Therefore, studies have taken on the task to solve these problems simultaneously through two means:

i. Developing and using alternative energy sources (particularly renewable energy sources)

ii. Improving the energy efficiencies in the fossil fuel-using equipment/systems

The fossil fuels are among the main causes of environmental pollution, whereas natural gas is an environmentally-friendly alternative. Not using fossil fuels and, hence, not contributing to global warming render heat recovery one of the most viable sources for energy production. The waste heat recovery process contributes both to the conservation of energy and abatement of thermal pollution. It is also used to heat buildings, preheat the plant processes, and produce electricity. Figure 1.1 displays the diagrammatic representation of the dispersion of the energy sources of electricity production in Turkey, 2017.

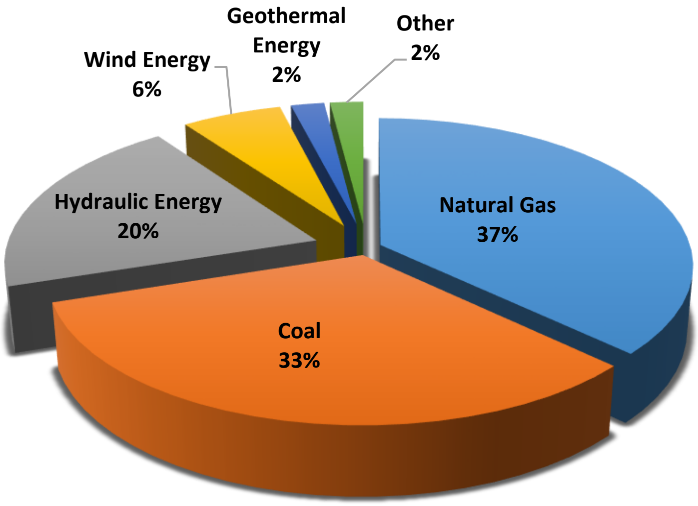

Figure 1.1. Diagrammatic representation of the dispersion of the energy sources of electricity production in Turkey (Anonymous, 2017)

Cogeneration is the successive generation of two different useful energy forms based on a main energy source. The energy can either be electrical and thermal or mechanical and thermal and the sequences of generation can include any combination of these energy forms. It is well-known for its high energy efficiency and provides two of the required energy forms in the same quantity as each other in addition to its advantage in minimizing the primary energy cost. It meets the same power and heat requirements as a conventional energy supply system by consuming significantly lower amounts of primary energy than does a conventional system in which power and heat are produced separately. The combined production feature of cogeneration reduces the production costs of the economies of scope and emerges as a critically important criterion to consider in improving the efficiency of the currently available cogeneration systems. Cogeneration produces heat and work through the use of a single fuel to meet the energy use of a system. Cogeneration systems result in increased energy efficiency and decreased environmental pollution. Moreover, increasing the efficiency of systems is cost-friendly, rapid, and easily applicable. Thus, the analysis of the performance, especially the effective loss and irreversibility analyses, is of fundamental importance in the improvement measures. Within this scope, exergy term and exergy analyses have become vital. Exergy analyses are an indispensable tool to design, analyze, and optimize thermal systems. Its application to an extensive range of energy systems has been successful. It provides necessary information when choosing a suitable component design and operation procedure. The information provided by exergy analysis contributes much more greatly to the evaluation of plant and operating expenses, fuel resourcefulness, and pollution. In addition to its potential for improving the energy efficiency of systems, exergy analysis enables the description of the enormities and localities of exergy destructions (irreversibility) inside the entire system. Figure 1.2 shows the diagrammatic representation of a cogeneration process and Figure 1.3 shows the diagrammatic representation of the sectoral distribution of cogeneration systems in Turkey.

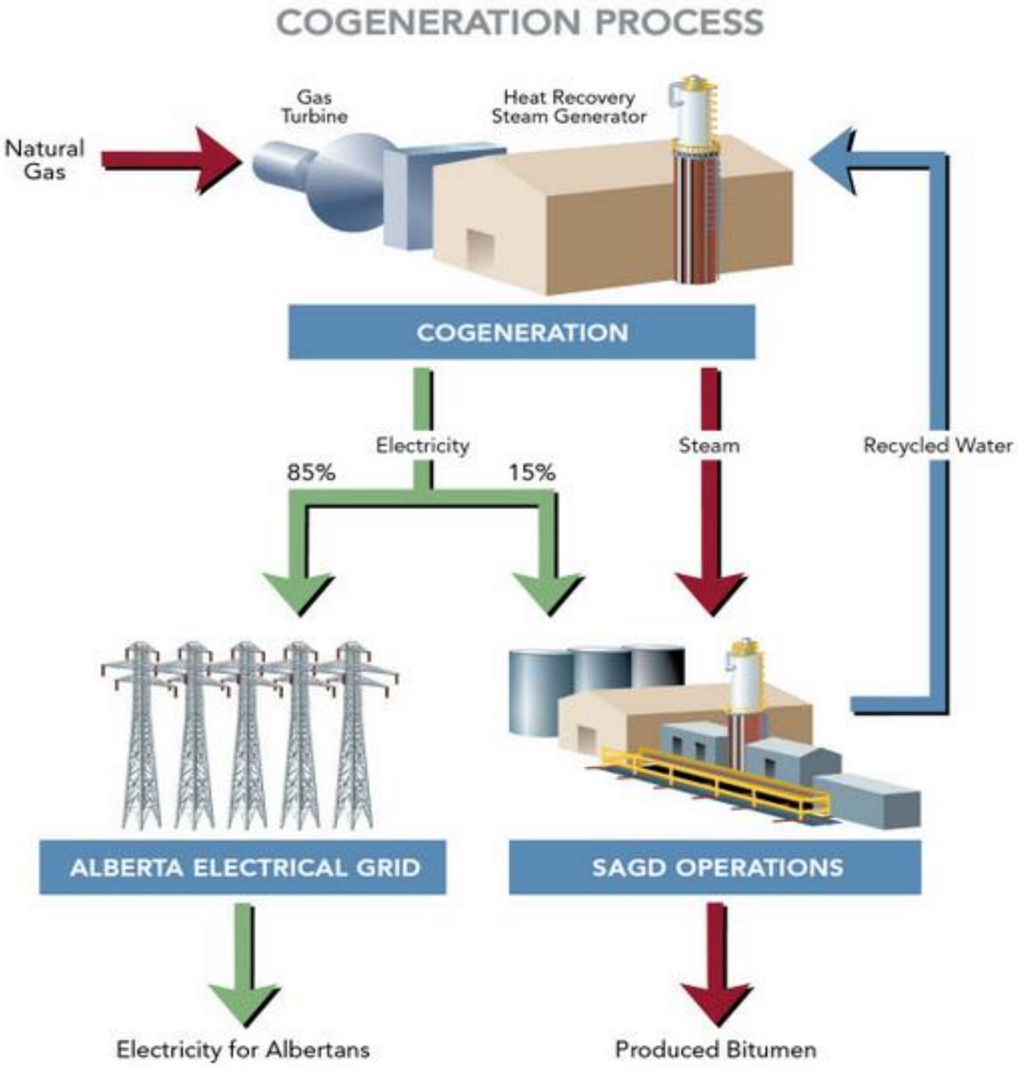

Figure 1.2. Diagrammatic representation of a cogeneration process (Anonymous, 2017)

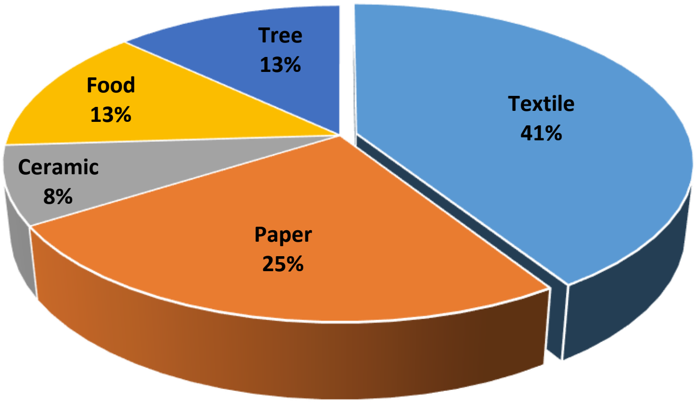

Figure 1.3. Diagrammatic representation of the sectoral distribution of cogeneration systems in Turkey (Anonymous, 2017)

Cogeneration is among the most important methods in the efficient use of fuels along with its contribution to the savings in natural and financial resources and protection of the environment. Various countries have taken on the task to overcome the obstacles arising out of its use and promote its widespread use. The relatively high prices of the surplus power purchases from power corporations and investment subsidies are among the implementations to promote its use. Cogeneration systems having reciprocally working internal combustion engines are divided in three categories: (a) small scaled unit with gas or diesel engine, (b) moderate size capacity systems (1000 – 6000 kW) with diesel or gas engine, and (c) high capacity system (higher than 6000 kW) with diesel engine. Diesel engine can be classified under three categories; ‘‘high-speed”, ‘‘medium-speed”, and ‘‘low-speed”. Most of the distillates of the oil are considered appropriate for use as fuels and relatively heavier oil distillates are utilized in engines with a larger size. The Turkish private power manufacturing sector uses diesel engine plants in regions without a natural gas supply. Diesel engines have certain advantages such as shorter installation periods, higher levels of efficiency, and more power to heat ratio than those of other main mover elements including steam or gas turbines. Using the heat from the engine and energy of exhaust gases, the diesel engine-powered cogeneration systems supply the hot water and steam requisite of manufacturer sites. Figure 1.4 shows the diagrammatic representation of a cogeneration plant.

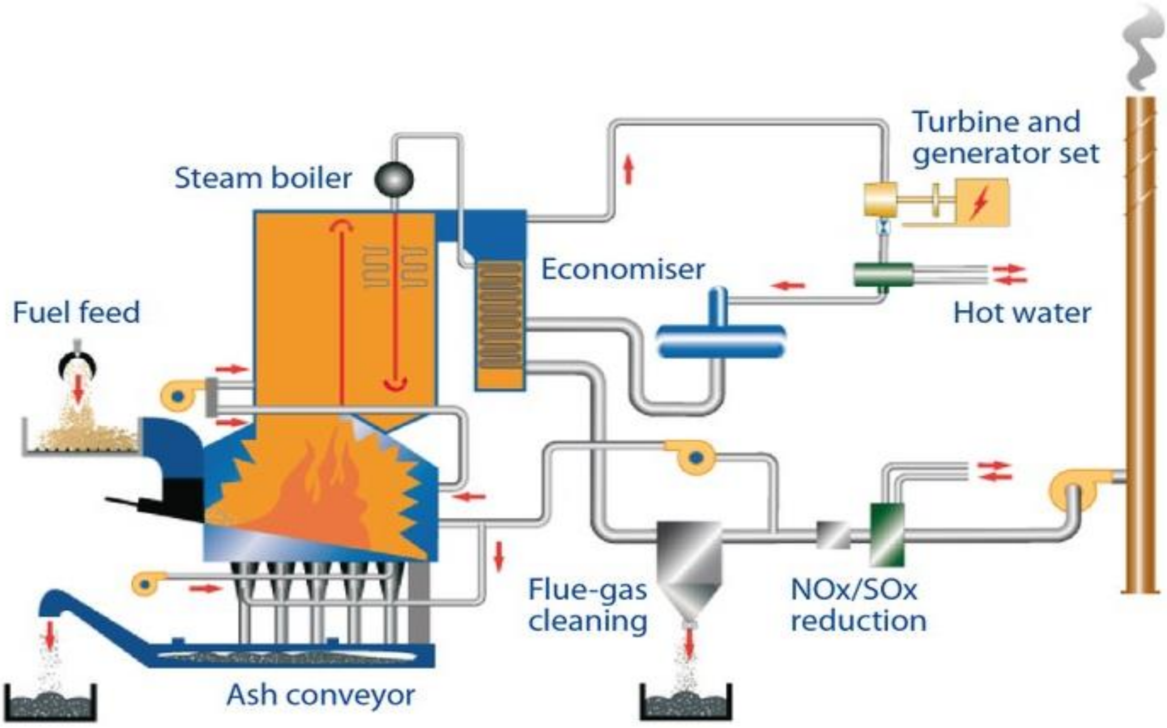

Figure 1.4. Diagrammatic representation of a cogeneration plant (Combined Heat and Power) (Anonymous, 2010)

Thermodynamic can be described as study of the relationships of heat, work, temperature, and energy. In a broader context, thermodynamic is concerned about the conversion of energy from and to other forms of energy and the transfer of energy from one location to another. Accepting heat as an energy form that corresponds to a definite value of mechanical work is the most fundamental concept of thermodynamics. Figure 1.5 shows the diagrammatic representation of the thermodynamic laws.

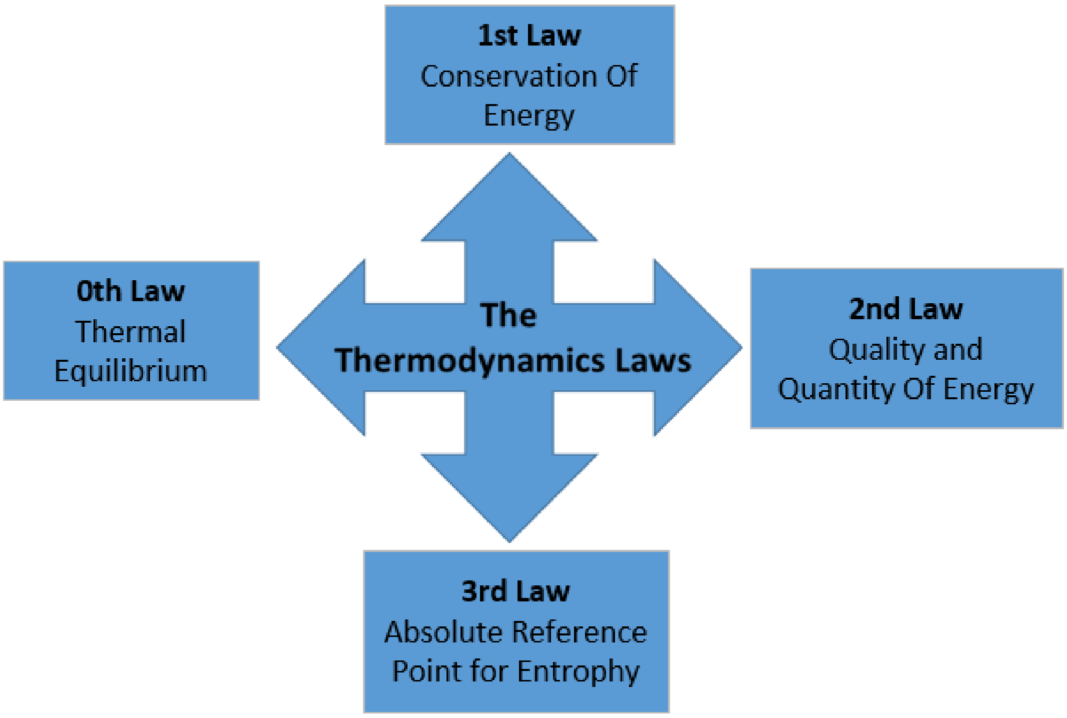

Figure 1.5. Diagrammatic representation of the thermodynamics laws

The fundamental laws of thermodynamic are:

i. *The 0th law of thermodynamic.* Two systems are in thermal equilibration where both systems are in thermal equilibration with a third system. This property allows use of thermometers as a “third system”, can be described “a temperature scale”.

ii. *The 1st law of thermodynamic.* Distinction between the heat entering to the system from the ambient and the work made by the system to its surrounds equals to the change in the internal energy of system.

iii. *The second law of thermodynamic.* The flow of heat from a less warm region to a hotter region is not spontaneous, or, correspondingly, the complete conversion of heat into work is not likely at a given temperature. Thus, heat energy per unit temperature or the entropy of a closed system gradually rises towards a maximum value. Thus, all closed systems are disposed to reach an equilibrium state, which is a state of maximum entropy in which the energy required to produce useful work is not available. The asymmetry between forward and backward processes leads to the asymmetry of time, which is also denoted as “arrow of time.”

iv. *The 3rd law of thermodynamic.* The entropy of a crystal of an element in its steady phase has a tendency for reaching zero as the temperature approximates absolute zero, which, from a statistical point of view, allows establishing an absolute scale for entropy to determine the degree of randomality or irregularity in a system.

The need for optimizing the performances of steam engines brought about the rapid development of thermodynamics during the 19th century but the all-embracing applicability of the laws of thermodynamics to physical and biological systems renders their use all the more prevalent. The laws of thermodynamics describe the modifications in the energy state of a system and the ability of the system to do beneficial work on their environments.

Exergy is measured as potential of a stream to give rise to a change, stemming from the deviation of the stream from complete stability in terms of a reference environment. It is described as the maximum work producible by stream of matter, heat, or work as the stream reaches equilibration with a referred environment.

Exergoeconomic analysis can be described as a mixture of the exergy and economic analyses and has a great potential in the optimization of the systems through the use of the efficiency of energy and exergy. The goals of exergoeconomic analyses include: (Ozdil and Tantekin, 2017)

i. Separately calculating the expenses of each produced item generated by a multi-product system,

ii. Giving an insight into the expense formation procedure and the flow of the expenses in a system,

iii. Separately optimizing specific parameters regarding the components, and

iv. Optimizing the overall system.

CHAPTER 2. LITERATURE REVIEW

Bade and Bandyopadhyay (2015) stated that combined heat and power (CHP), is of importance both for improvement of the energy efficiency of entire plant and reduction of environment pollution. The researchers proposed a pinch analysis-based method in which a gas turbine and a regenerator were combined with a process plant to decrease fuel consuming to minimum. In the study, a methodology was introduced to directly integrate a gas turbine and regenerator inside the process plant. Related results revealed that the optimum pressure ratio to achieve the highest value of power plant efficiency was less than the limit pressure ratio at which the net-work reaches its highest value. Thus, the researchers concluded that a compromise between the efficiency of gas turbine plants and size and weight may be necessary. They emphasized that a gas turbine power plant designed to obtain maximum power plant efficiency at an optimum pressure necessitated the use of a maximum specific network-producing system, a high compressor ratio, and a low power plant efficiency in addition to requiring larger sizes and capacities because of its lower specific clearance.

Bonnet et al. (2005) argued that hot-air engines (Stirling and Ericsson engines) were highly appropriate to use in micro cogeneration because of their noiseless operating conditions and low maintenance requirements. Ericsson engines (in other words, external heat-supplied Joule-cycle reciprocating motors) are more interesting because their designs are less restricted and potentially cheaper than Stirling engines, and they have shown that they provide better systems for energy. They have examined the relationship between the Ericsson engines and a natural gas combustion system. The conventional energy, exergy, and exergoeconomic analysis were made to design the system. Researchers presented the results they obtained from the analyses and their evaluations for the cost of the cogeneration system. The energy analysis performed in the study helped the designing and dimensioning of the plant and allowed the testing of the effects of heat exchangers on the productivity and cost for raw materials. The researchers noted that the proper evaluation of the activity of each heat exchanger was important in obtaining better efficiencies, avoiding large transfer surfaces, and minimizing costs. The analyses allowed finding an appropriate compromise among efficiency, heat transfer area, and heat exchanger costs. Through the exergy research, a diagram was drawn and the exergy flows and exergy destruction in the system were observed. The study aimed to shed a new light on an old, yet cost-friendly, easy, and productive technology and invigorate the Ericsson engine that faces undue negligence.

Orhan et al. (2009) investigated the production of core-based hydrogen through thermochemically obtained water separation utilizing a copper-chlorine (Cu-Cl) cycle in which water is separated to hydrogen and oxygen after some chemical reaction. The cycle comprises five phases including three thermal and an electrochemical reactions: (1) production of HCl (g) using equipment such as fluidized beds, (2) O_2 production, (3) Cu production, (4) drying, and (5) hydrogen production. Each section involves a chemical reaction, except for the drying process. In this study, production of HCI (g) and the effects of its operation and environment states on the Cu-Cl cycle were described; comprehensive thermodynamic analysis was performed using the related chemical reaction. The performance of the fluidized bed was investigated using energy and exergy efficacies in addition to the parametric studies in which different reactions, reference ambient temperatures, and energetic and exergetic angles were used. Parametric studies yielded information about the effect of the reaction temperatures and the referred ambient temperature values on the reaction heat, entrance and exit gas, exergy destruction, and exergy efficiency. To obtain lower product expense and improve the monetary practicability of the process, the researchers recommended using the outcomes taken from energy and exergy analysis in exergoeconomic analysis and optimization of process.

Nemati et al. (2017) compared the Organic Rankine Cycle (ORC) and Kalina Cycle (KC) with each other using thermodynamic modeling and optimization to reveal their advantages as bottoming cycles for waste heat recovery in CGAM cogeneration systems. The models were developed for the CGAM / ORC and CGAM / KC systems and the effect of certain decisive factors on energy and exergy yield and turbine dimension parameters were examined. The results showed that the optimization of the 1st and 2nd law efficacies at a certain pressure ratio and the minimization of the bottoming cycle net output power and TSP were achieved through changing the air compressor pressure ratio. An increase in the temperature of the pinch spot reduced the energy and exergy efficacies, cyclic power generation, and TSP. The energy and exergy efficacies, energy production, and TSP increased with increasing concentrations ofammonia in the circulation. The energy and exergy efficiencies of the CGAM / ORC system was higher than those of the CGAM / KC, indicating that ORC is preferable over KC in the waste heat recovery from CGAM.

In their study, to evaluate the yield composition of a biomass gasification system utilizing extremely pre-heated air and steam, Wu et al. (2014) developed a chemical equilibrium model and discussed the advantages and limitations of the system in terms of thermodynamics. The analysis of the first and second law of thermodynamic were performed for different pre-heating temperature and steam / biomass mass (S / B) ratios. Under these conditions, the highest chemical energy output from the obtained synthesis gas was maintained when the S / B ratio was 1.83 but as the S / B ratio increased, so did its negative effects on the energy and exergy efficiencies. The researchers determined that chemical energy and energy and exergy efficiencies increased with increasing preheat temperatures and the highest values of energy and exergy efficiencies were 81.5% and 76.2%. In view of the highest values obtained for the efficiencies, Wu et al. identified a possible thermodynamically probable study area and proposed a practical study area for industrial applications.

Kumar (2017) provided an insight into the opportunities for future research on thermal power plants. The researcher asserted that the increasing energy supply-demand has drawn attention to the efficiency of the equipment and the optimization of existing thermal power plants. Kumar stated that the energy balance of the system is not always sufficient to detect system inadequacies and energy losses occurring in a system may easily be detected by an exergy analysis. The researcher pointed to exergy analysis as a capable tool for measuring energy quality and stated that it can help increasing the efficiency of complex thermodynamic systems. The studies in which the thermodynamic analysis of Rankine cycle in coal-fired power plants was performed have revealed that highest energy loss had occurred in the condenser. Great excavation was found on the damage. The studies have also explained that the cost of the exergy destructions in boilers and turbines was greater than that of the exergy destructions in other components. In the studies carried out in gas-fired power plants, the burners were determined to have the lowest efficiency and pointed out as the largest exergy destructor. Using both classical and exergetic analysis, the combustion chamber was determined to be responsible for the highest exergy destruction. Since supercritical, ultra-supercritical, and advanced super critical cycles have not been much focused on energy and exergy analysis until now, since gambling, material used cannot withstand very high pressure and temperature.

Can et al. (2009) examined exergy and economic analysis based on the values acquired during the study period of a cogeneration facility system in Turkey. The first and second laws of thermodynamics have been modified to the measured values to find the fuel efficiency, power-to-heat ratio, and process heat ratio. The system is thought to be a stable state open system. Conclusively, efficiency of second law was 89.5% and the payback duration of the facility was 3.5 years. These values are the appropriate efficiency and time interval for good designed plants from the perspective of economic analyses. Can et al. have obtained the result that the installation of cogeneration system may find more industrial utilization because of the reduction of energy and oil reserves in the future.

Puadian et al. (2014) developed an integrated system model for a rotary biomass dryer utilizing a combined use of a dual-fluidized bed (DFB) biomass gasifier and user-defined and internal unit operations at UniSim Design. A quasi-equilibrium model was employed to model the biomass vaporization gasification in the DFB gasifier. The energy and mass balance, dryer configuration and heat transfer were used to simulate the biomass. Following the evaluation and validation of the model using the experimental data, the model was used in the investigation of the impact of the steam to biomass (S / B) rate and the gasification temperature on the gasification implementation and the impact of the air fed to the fast fluidized bed (FFB) reactor and biomass humidity content on the combined system capacity. The results revealed that the gasification warmth and the S / B ratio positively affected the gasification efficiency. Puadian et al. reported that a higher air procurement to the DFB gasification was relatively favorable if the drying biomass had higher moisture content, which is attributable to its increased requirement for flue gas, however flue gas at a lesser temperature was suitable for use in the biomass dryer. Thus, more steam with a higher combustion gas rate is produced and energy efficiency is not much influenced as opposed to the decrease in exergy, which is due to the considerably lower exergy of the excess fuel than that of the steam produced in the system.

Yildirim and Gungor (2012) stated that the exergoeconomic analysis was among the most prevalently used exergy sub-methods in which exergy analyses and economic analyses are combined. Considering a prior exergetic analysis of a CHP system with a aggregate electric power of 11.52 MW and steam generation capacity of 9.0 ton / h at 140.5C, the researchers proposed a suitable location for cost-based information and CHP system enhancement. An analysis based on the Specific Exergy Costing (SPECO) methodology was performed and the calculations showed that the specific unit exergy cost of the electricity generated by the CHP system was US Dollar 4.48 / GJ. The study revealed that the information provided by the exergoeconomic analysis was more extensive than that by the exergy analysis and could offer exergoeconomic locations suitable for the improvement of the CHP system, which, in turn, will escalate total efficiency of the system through the identification of the main loss sites and thereby obtaining an optimized process.

Özdemir et al. (2010) conducted an exergoeconomic analysis adopting actual operational data based on a fluidized-bed coal combustor (FBCC) steam power plant in İzmir, Turkey. The sub-systems of the plant include a ventilation fan (VF), a FBCC, a heat recovery steam producer (HRSG), a cyclone (CY), an economizer (ECO), an aspiration fan (AF), a pump (P), and a chimney (CH). A comprehensive exergoeconomic analysis study has been conducted with FBCC steam plant's basic subsystems including VF, FBCC, HRSG, CY, ECO, CH, and P. The researchers stated that, as an analysis yielding cost-based information, the exergoeconomic analysis provided more information than the exergy analysis. The researchers recommended placing an air preheater factory among the VF and FBCC for the minimization of the utilization of exergy in FBCC.

Gurturk and Oztop (2016) performed the energy and exergy analysis of a cogeneration facility. The most important component in the cogeneration power plant was a circulating fluidized bed boiler (CFBB), also a steam generated by the cogeneration power unit was utilized in salt manufacturing. The CFBB had an energy yield and exergy yield of 84.65 % and 29.43 %, while the mean exergy yield of the boiler was 43.58%. The exergy yield of CFBB was relatively lower than that of similar boilers. The exergy damage of the CFBB was determined to be 21789.39 kW and equaled to 85.89% of the exergy damage in the CFBB. Using fuels with low combustion efficiency resulted in increased entropy production. Moreover, the balance ratio and combustion yield of the CFBB were calculated to be 1.053 % and 69 %. The power plant had an exergy efficiency of 20%. The analysis results revealed that optimization was required for the CFBB in addition to the need for the re-evaluation of certain design parameters.

Kamate and Gangavati (2009) evaluated the exergy analyses of the heat-matched, bagasse-based cogeneration plant of a 2500 tcd (tons of cane per day) sugar factory in which a back-pressure steam turbine and subtraction condensing steam turbine were used. Coupled with more general energy analyses, total and component efficiencies were evaluated using the exergy methods along with the determination of thermodynamic losses. A boiler with contemporary properties can only use 37 % of the chemical exergy of the fuel in steam production and the boiler-related combustion irreversibilities are lost by 63%. Hence, exergetic efficiency of the boiler is open for improvement. Moreover, the exergetic efficiency of the boiler improves significantly with increasing input conditions of the HP steam. Therefore, steam production temperature and pressure can be increased to minimize exergy losses and improve exergetic efficiency.

Ozdil and Tantekin (2016) conducted a study to provide an elaborate exergy and exergoeconomic analysis of an electricity generation system using biogas engine in a treatment of wastewater plant in the city of Adana. The system comprised a compressor, a turbine, four heat exchangers, a pump, and a gas engine. How the exergic and exergoeconomic parameters of the system were affected by the components was investigated separately for each component. The results revealed that the highest exergy destruction was 4055.31 kW and occurred in the gas engine, followed by the exhaust gas heat exchanger (EGHE) and lubricating oil exchanger (LOHE) with exergy destruction values of 99.86 kW and 92.64 kW, respectively. Exergy efficiencies of compressors, turbines, pumps, BGHE, LOHE, WHE, EGHE, and gas engines were determined to be 76.50%, 78.43%, 6.49%, 13.40%, 11.56%, 60.44%, 67.36%, and 50.79 %. The exergy destruction rate was 4341.03 kW, while the exergy efficiency of the plant was 69.10%. The researchers mainly attributed the inadequacy of the system to the high temperature differences in chemical reactions occurring in burnout process, the amount of excess air, the sort of biogas, heat exchangers, and high levels of heat release by the chemical reactions in the combustion process leading to increased irreversibility in the system. An excessive increase in the air causes increases in mass flow rate of combustion gas, which results in increased heat loss in the system and, thus, decreased efficiency. The change in the biogas content used in the gas engine results in varying proportions of exergy destruction because of the different calorific value of the fuels as well as causing high temperature variations in the heat exchangers, that also causes exergy destruction. It is proposed to reduce the temperature differences between fluids or to keep fluids used in heat exchangers at lower temperatures to reduce damage to the system. The gas engine had the lowest exergoeconomic factor by reason of the high exergy destruction rate in the engine. The researchers argued that heat exchangers with a high exergoeconomic factor entail higher operation and maintenance costs and stated that the results of the study will be of benefit to the exergoeconomic optimization of the wastewater treatment plant.

Abusoglu and Kanoglu (2009) carried out the thermodynamic analyses of a diesel engine cogeneration system located in a plant in Gaziantep, Turkey. The exergy destruction in each component was evaluated separately also the determination of the exergetic efficiencies. The thermodynamic performance of the 25.32 MW diesel engine cogeneration system with a steam capacity of 8.1 ton / hour was determined to be 44.2% and 40.7% under full load conditions. The researchers recommended using the information obtained in the study in the designing of recent energy-efficient systems and improvement of the efficiencies of the current systems. They have concluded that the results presented in the study can serve as a powerful and systematic instrument in the determination of the cost-increasing parameters and optimization of the diesel engine cogeneration systems.

Lee et al. (2014) emphasized that it is important to have a stable estimation of the power production capacity of every power plant in an electric grid, and to manage the grid in a stable manner by preventing the incompatibility between electricity demand and energy generation. This estimate also helps protect the power plant proprietors' institutions as it permits for efficacious performance watching. Using the integration of correcting curves and thermodynamic non-design modeling, the expected power output was calculated and unique two-step logic was established to forecast future power generation capacity using a measurement-based power correction factor. A logic-based simulation program has been developed and approved. The basic property of this logic is to find the power correction factor by comparing the actual power and the anticipated power output. In other words, it is significant to simulate the performance degradation using the plant's actual operation data. In general, the feasibility and practicality of the suggested method has been verified. The improved logic should be used for performance monitoring as well as electricity production capacity for electricity trading and for the identification of different types of power plants.

Gholamian et al. (2016) introduced a novel cogeneration system comprising a biomass gasifier, a gas turbine, a S-CO2 cycle, and a domestic water heater. Using the engineering equation solver (EES), the mass, energy, and exergy balances were applied to each system component and the performance of the system was simulated. The majority of the irreversibility in the system was attributed to the combustion chamber and gasifier. The parametric study showed that the pressure ratios of the gas turbine and the S-CO2 turbine significantly affected the performance of the system. Additionally, the environmental impact of the system was assessed in terms of CO2 emission by considering the system as a combination of three sub-systems: an independent gas turbine, the entire system without the water heater and the cogeneration system. The air preheater was determined to be the main contributor to the irreversibility in the system. The results obtained for the ecological effect of the system revealed that the CO2 emissions of the cogeneration system was relatively lower in addition to its better efficiency than that of the power production system and independent gas turbine.

Mert et al. (2012) conducted an exergoeconomic analyses of a cogeneration plant located in Edremit. In the research, the exergoeconomic analyses of the 39.5 MW-electricity and 80 ton/h steam generation-capacity plant was done and the mass, energy and exergy balances were implemented to the system.

Kim et al. (1998) suggested an approach for the combined exergy and thermoeconomic analysis of complex energy systems. In the study, an overall expense-balance calculation applicable to every unit of a thermal system was developed. The exergy of a material flow was divided into thermal, chemical and mechanical exergy flows and an entropy-production flow. Each exergy flow was appointed to a unit exergy cost, without regard to the type of the exergy stream and the state of the stream. Thus, a equations for unit costs of different exergies was obtained through the application of the cost-balance equation to each component and junction of the system. The equations were solved to financially evaluate the costs of different exergies (thermal, mechanical, etc.) and costs of the electric made by the thermal system. Method also allowed determining the lost costs of each component. Furthermore, as a method providing information for use in the design and operation of the cogeneration system, the exergy-costing method developed by the researchers was employed in the evaluation of a 1000-kW gas turbine cogeneration. Allocating costs for each exergy component allowed expressing the cost of the exergy of the yield for a system component with reference to other appointed exergy costs and the unit costs of added or removed exergies in the stream. The exergy-costing method provided information about the actual production process within the system. The application of the method to a gas-turbine cogeneration system revealed that the unit exergy costs increased as the production process continued and the increase in the electricity production cost was almost proportional to the input cost.

Santos et al. (2016) analyzed the biogas combustion and energy recovery processes from a thermodynamic, exergetic and thermoeconomic viewpoint. Regarding its competitive advantages and potential for extensive use, the researchers investigated whether biogas biomethanisation from the primary and secondary treatment of the activated sludge obtained from a wastewater treatment plant (WWTP) could be an option to fossil fuels as a renewable energy source. The researchers asserted that the use of biogas biomethanisation will bring about compliance with the highlights of the energy plans of the EU countries, which include the minimization of the amounts of CO2 emissions and the organic matters deposited in landfills as well as offering effective answer to reduce the environmental effect of sewage sludge. The results of the study unclosed that the majority of the irreversibility and exergy destruction was due to the process boiler. Furthermore, the exhaust gases released from the combustion chamber was determined to be economically valuable and thus, the practicality and suitability of integrating a Stirling engine into the process were investigated. The study demonstrated that creating a small-scale micro-cogeneration system was achievable and beneficial due to its contribution to sustainable waste management and energy savings in the treatment plant itself.

Uysal et al. (2017) performed the exergetic and thermoeconomic evaluation of a 160 MW-capacity power plant working with coal as source material in Turkey. The Specific Exergy Costing and Modified Productive Structure Analysis implementations were apart employed to reveal the unit exergy cost of the electricity produced by the coal-fired plant and the techniques were compared with each other. The results revealed that the exergy efficiency of the coal-fired power station was 39.89%. The boiler was determined to be the equipment with the highest potential for improvement. The unit specific exergy costs of the electricity generated by the system were determined to be 12.14 US Dollar/GJ and 14.06 US Dollar/GJwith the SPECO and MOPSA methods, respectively, which indicated that the unit specific exergy cost of electricity as determined with the MOPSA thermoeconomic technique was almost the same as the cost determined with the overall cost-balance equation for the coal-fired power plant.

Compared with other fossil fuels, thanks to the relatively longer lifetime of the coal reserves and resources, the coal-fired power plants will be of long-term benefit to the electricity production in Turkey and worldwide. Because of their contribution both to the national budget and to the reduction of air pollution and along with their longer lifetime, the assessment and development of the performance of the coal-power plants and their cost-effective operation are of great importance. In the study, a coal-fired power plant in Turkey was examined by considering each related component. As two different thermoeconomic analysis techniques, the specific exergy costing and changed productive structure analysis techniques were applied separately to the system. The exergy analysis revealed that the steam boiler and condenser were the components of critical importance in the development of the system performance.

Using the SPECO and MOPSA methods, the unit specific exergy cost of the electricity generated by the system was determined to be 12.14 USDollar/ GJ and 14.06 US

Dollar/GJ, respectively. The difference between the results was attributed to the differences in the principles and assumptions of the methods. In the SPECO method, a unit cost is appointed to each material in a stream at a given state, while, in the MOPSA method, a unit cost is appointed to each exergy without regard to the state of the stream. For example, in the study, for the analysis of the water stream in the condenser with the SPECO method, the unit cost of the water stream at the entrance was supposed to have a null value for the calculation of the unit cost of the water stream at the exit, while in the case of the MOPSA method, the unit exergy cost of the water stream in the condenser was calculated using the exergy difference between the entrance state and exit state. In the MOPSA method, the flow rates of the water leaving the condenser and the combustion gas leaving the air preheater had greater costs than that of the flow rate determined with the SPECO method; thus, the production cost calculated with the MOPSA method was higher than that with the SPECO method.

The product cost of the system may be reduced by not dividing thermomechanical exergy into its components. However, especially in equipment-based assessments, this strategy doesn’t yield exact detail about the cost structure of the system. Furthermore, this type of analyses has a poorer accuracy in the estimation of the unit specific exergy cost of the electricity producted by system. The SPECO method requires using same number of equations as the number of the system states for every material stream, whereas in the MOPSA method, the number of equations is almost the same as the number of equipment. Hence, the MOPSA method is preferable in the analysis of complex and large thermal systems. In addition, the MOPSA application accurately determines the unit expenses of the system.

The scientific literature includes several studies on the thermoeconomic analysis methods; however, every approach possesses different features and increasing number of different thermoeconomic analysis methods further complicate the discourse. Thus, to reduce the number of methods, future studies should focus on the development of a common thermoeconomic analysis method that includes the advantages offered by the current methods.

Silveira et al. (2002) applied a thermoeconomic analysis method to a cogeneration systemin a college site to determine the feasibility of replacing the gas turbine in the system. The system comprised a gas turbine attached to a waste boiler. The electricity demand of the campus was approx. 9 MW, although it only met about one third of the electricity demand of the campus and generated approx. 1.764 kg/s saturated steam (at 0.861 MPa) from only one fuel source. The thermoeconomic study revealed that, according to the pay-back period, the system containing the gas turbine ‘‘M1T-06’’ procured from Kawasaki Heavy Industries was the best technique, followed by the system containing the gas turbine “M1T-03” procured from Kawasaki Heavy Industries. According to 10-year savings, the best systems were the systems containing the gas turbine ‘‘CCS7’’ procured from Hitachi Zosen and the gas turbine “IM400” procured from Ishikawajima–Harima Heavy Industries, respectively. Instead, according to the exergoeconomic analysis, the best system, in other words the system with the lowest EMC, was the system containing the gas turbine ‘‘ASE50’’ procured from Allied Signal, followed by the system containing the gas turbine‘‘IM400 HI-FLECS’’ procured from Ishikawajima–Harima Heavy Industries. The researchers concluded that the design and operational parameters of the system were of importance in the evaluation of the cogeneration systems and after having overcome the initial complications, the EMC method could prove a good instrument for optimizing of a cogeneration system. Since this method is a direct algebraic method by nature, its advantages include its low computational time, ease of handling, and allowing changes in the parameters when needed.

CHAPTER 3. MATERIALS AND METHOD

3.1. System Description and Assumptions

Before moving on to cogeneration plant analysis, it might be useful to present an extensive introduction of the system components. The power plant is situated at Adana, Turkey and has a capacity of 14.25 MW. The major components of the plant include a boiler (B), an economizer (ECO), a turbine (TE), four ventilation fans (VF), a chimney (CH), and two pumps (P). Figure 3.1 illustrates the representation of the cogeneration system in the plant.

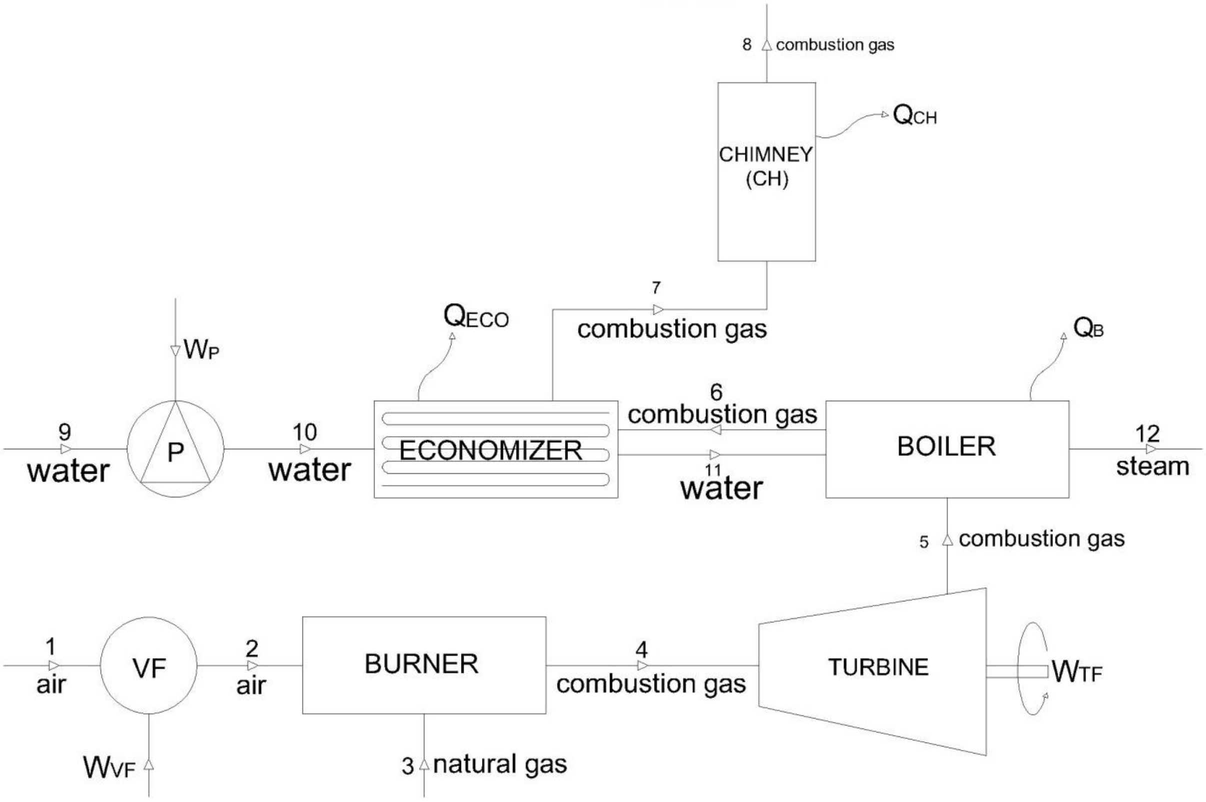

Figure 3.1. Graphic illustration of the power plant

The steam capacity and steam pressure of the boiler are 25 t/h and13 bar, respectively. The four ventilation fans have a total capacity of 46000 m3/h (30 kW) and supply the combustion air to the burner. Natural gas is the fuel of the cogeneration system and its composition is given in Table 3.1. The boiler and economizer have horizontal and vertical heat exchangers. Table 3.2. shows the operating conditions of the cogeneration system. The feed water pump has a capacity of 83 kW (25 t/h) and the steel chimney hasn’t isolation material. First, the feed water is pumped into the economizer and, then, passes through the boiler in which steam generation takes place using the heat exchanger tubes inside the boiler.

Assumptions of this study are:

i. The plant functions in a steady mode.
ii. The idyllic gas principles are accepted for the air and combustion gas.
iii. The pressure losses in the piping system and ducts are ignored.
iv. Kinetic and potential energy are neglected.
v. A classic boiler is utilized in the system.
vi. The physical exergy of the fuel was neglected.
vii. Adiabatic conditions are assumed for the turbine.

Table 3.1. The composition of the natural gas (Ozdil and Pekdur 2016)

Component	Formula	Volume fraction (%)
Methane	CH_4	98.680
Ethane	C_2H_6	0.211
Propane	C_3H_8	0.043
Butane	C_4H_{10}	0.017
Pentane and others	C_5H_{12}	0.035
Carbon dioxide	CO_2	0.035
Oxygen	O_2	0.000
Nitrogen	N_2	0.829

		(kcal/kg)
GCV/HHV		13,459
LHV		12,132

Table 3.2. Operating conditions of the cogeneration system

Mass flow rate (Natural gas)	0.5179 kg/s
Flow rate (Steam)	22 t/h
Steam pressure	12 bar
Steam temperature	190 ^{o}C
Flow rate (Combustion gas)	40.21 kg/s
Flow rate (Air)	46,000 m^3/h
Flow rate(Water)	22 t/h

3.2. Analysis

The main principle of the cogeneration system is to generate heat and work utilizing a only one fuel to improve the energy consumption of the system.The study investigates the most and least effective components of the cogeneration system by performing the energy and exergy analyses of the system. According to the first and second law of thermodynamic, the thermodynamic efficacies of the cogeneration system are given as energy and exergy efficiencies. Figure 3.2. shows illustration of the components of cogeneration plant. Using the related thermodynamic tables and EES software, the thermodynamic features of the water, steam, and combustion gases were determined for use in the calculations. The thermodynamic properties of the reference environment were accepted to be $T_0 = 25\ ^oC$ and $P_0 = 101.3$ kPa. The temperature measurement was performed with the TESTO 435 measurement device with a NiCr-Ni, K-type thermocouple in the ranges of -60, +300 ^oC, and 0.5 ^oC sensitivity. The portable TESTO 350 device for combustion gases was employed in the determination of the composition of the combustion gases released by the chimney. Table below shows the mole fractions of the combustion gases.

Table 3.3. Composition of the combustion gas (Ozdil and Pekdur 2016)

Combustion Gas	Mole fraction (%)
NO	11.68
NO_2	17.91
CO	6.36
O_2	15.5
CO_2	48.55

3.2.1. Energy analysis for the system components

Mass and energy equilibration equations for the energy analysis are given by (1) and (2):

Mass Inlet = Mass Outlet $(\Sigma\ \dot{m}_{in} = \Sigma\ \dot{m}_{out})$ (1)

Energy Inlet – Energy Outlet = Net Energy $(Q + W = \Sigma\ \dot{m}_{out}h_{out} - \Sigma\ \dot{m}_{in}h_{in})$ (2)

a) Energy equilibration equation for the adiabatic turbine is given by (3):

$$E_4 = E_5 + W_{TE} \qquad (3)$$

b) Energy equilibration equation for the conventional boiler is given by (4):

$E_5 + E_{11} = E_{12} + E_l$ (4)

$E_l = E_{cg} + Q_{loss}$ (5)

$E_{cg} = \dot{m}_{fuel}\overline{m}_{cg}\overline{C}_{p\text{-}cg}\ (T_{comb} - T_0)$ (6)

E_l, E_{cg}, and Q_{loss} refers to the energy loss, the energy of the combustion gas, and the heat loss through the surface of the boiler via radiation.

A sample calculation can be seen below:

E_{cg} = 0,5179(kg/s) * 1,0092 (kg/s) * 44,3384 (kJ/kmolK) * (533 K-298 K)
E_{cg} = 5446,3059kJ/sn

$E_5 + E_{11} = E_{12} + E_l$
$\dot{m}_5\ h_5 + \dot{m}_{11}\ h_{11} = \dot{m}_{12}\ h_{12} + E_l$
40,2132 * 469,92164 + 6,11 *763 = 6,11 * 2789 + E_l
El = 6518,1993kJ/sn

$E_l = E_{cg} + Q_{loss}$
Q_{loss}= 5446,3059kJ/sn - 6518,1993kJ/sn
Q_{loss}=1071,8935kJ/sn

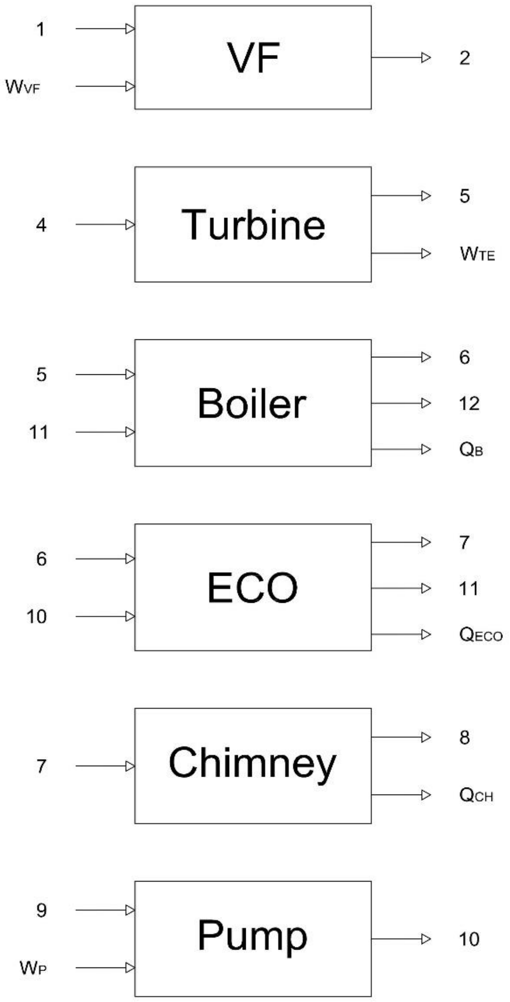

Figure 3.2. Illustration of the cogeneration plant (Ozdil and Pekdur 2016)

c) Energy equilibration of the economiser is given by Eq. (7):

$$\dot{m}_6 h_6 + \dot{m}_{10} h_{10} = \dot{m}_7 h_7 + \dot{m}_{11} h_{11} + Q_{loss} \qquad (7)$$

d) Energy equilibration of the chimney is given by Eq. (8):

$$\dot{m}_7\, h_7 = \dot{m}_8\, h_8 + Q_{CH} \qquad (8)$$

e) Energy equilibration of the pump is given by Eq. (9):

$$\dot{m}_9\, h_9 + W_P = \dot{m}_{10}\, h_{10} + Q_P \qquad (9)$$

f) Energy equilibration of the ventilation fan is given by Eq. (10):

$$\dot{m}_1\, h_1 + \dot{W}_{vf} = \dot{m}_2\, h_2 + Q_{Loss} \qquad (10)$$

3.2.2. Exergy analysis for the system components

General equilibration equations for exergy analysis are given by (11):

Exergy Inlet – Exergy Outlet – Exergy Destruction = Net Exergy (11)

A comprehensive exergy analysis of the cogeneration system was performed in order to reflect real-life thermodynamic performance of the system. The exergy analysis of cogeneration systems is performed separately for each component because of complexity of the cogeneration system.

The chemical exergy of the natural gas was found with Eq. (12):

$$ex_{ng}^{ch} = (LHV)^{*}\ \varphi_{dry} \tag{12}$$

where(LHV) and φ represent the lower heating value of the natural gas and the chemical exergy factor, respectively. Using the values given in Table 3.1., the chemical exergy factor of the natural gas is calculated with Eq. (13):

$$\varphi_{dry} = 1.0334+0.0183(h/c)-0.0694(1/Nc) \tag{13}$$

The general exergy formula to calculate the physical exergy (14):

$$ex^{ph} = (h - h_0) - T_0(s-s_0) \tag{14}$$

The chemical exergy of the combustion gas is calculated with Eq. (15-16):

$$Ex_{cg} = Ex_{cg}^{ph} + Ex_{cg}^{ch} \tag{15}$$

$$Ex_{cg} = \overline{\dot{m}}_{ng}{}^{*}[\ \overline{\dot{m}}_{cg}\{C_{p-mix}(T_{cg}-T_0)-T_0\ln(T_{cg}/T_0)+RT_0\ln(P_{cg}/P_0)\}+\dot{m}_{cg}{}^{*}ex_{cg}^{ch}] \tag{16}$$

The chemical exergy of the combustion gas (ex_{cg}^{ch}) can be calculated with Eq. (17)

$$ex_{cg}^{ch} = \Sigma\ x_i\ ex_k^{ch} + RT_0\ \Sigma\ x_i \ln x_i \tag{17}$$

$x_i$and ex_k^{ch} represent the volume fraction and chemical exergy of each combustion gas component (Table 3.3), respectively. R and T_0 represent the general gas constant and the ambient temperature, respectively.

With application of the 2nd law of thermodynamic to system:

a) Exergy equilibration equation of the turbine is given by (18):

$$Ex_4 = Ex_5 + W_{TE} + \dot{E}x_D \quad (18)$$

b) Exergy equilibration equation for the conventional boiler can be obtained as (19):

$$Ex_5 + Ex_{11} = Ex_6 + Ex_{12} + Q_B(1- T_0/T_S) + \dot{E}x_D \quad (19)$$

Sample calculation can be seen below:

$$Ex_5 + \dot{m}_{11}\, ex_{11} = Ex_6 + \dot{m}_{12}\, ex_{12} + Q_{loss}(1 – T_0/T_s) + Ex_D$$

$$42201{,}988 + 6{,}11 * 130{,}6844 = 36473{,}211 + 6{,}11 * 846{,}6764 + 1071{,}8935 * (1- 298/648) + Ex_D$$

Ex_D = 775,111385kJ/sn

c) Exergy equilibration equation for the economizer is given by (20):

$$Ex_6 + Ex_{10} = Ex_7 + Ex_{11} + Q_{ECO}(1- T_0/T_S) + \dot{E}x_D \quad (20)$$

d) Exergy equilibration equation for the chimney is given by (21):

$$Ex_7 = Ex_8 + Q_{CH}(1 – T_0/T_s) + Ex_D \quad (21)$$

e) Exergy equilibration equation for the pump is given by (22):

$$\dot{m}_9\, ex_9 + W_P = \dot{m}_{10}\, ex_{10} + Q_P.(1 – T_0/T_s) + Ex_D \quad (22)$$

f) Exergy equilibration equation for the ventilation fan is given by (23):

$$\dot{m}_1\, ex_1 + \dot{W}_{vf} = \dot{m}_2\, ex_2 + Q_{Loss}(1 – T_0/T_s) + Ex_D \quad (23)$$

3.2.3. Energy Efficiencies

Energy efficiencies can be described as the ratio of the energy outlet to the energy inlet and calculated with Eq. (24):

$$\eta_I = \text{energy outlet} / \text{energy inlet} = 1 - (\text{energy loss} / \text{energy inlet}) \quad (24)$$

a) Turbine

The energy efficiency of the turbine is calculated using the 1st law of thermodynamic. For this estimation, generated power (electricity) is considered as the energy input while energy difference between the inlet and outlet combustion gases can be accepted to be the energy outlet. The energy efficiency of the turbine can be given by Eq. (25):

$$\eta_{I,TE} = W_{TE} / (\dot{m}_4 h_4 - m_5 h_5) \quad (25)$$

b) The energy efficiency of boiler can be found using Eq. (26):

$$\eta_{I,B} = (\dot{m}_5 h_5 - \dot{m}_6 h_6) / (\dot{m}_{12} h_{12} - \dot{m}_{11} h_{11}) \quad (26)$$

c) The energy efficiencyof economizer can be calculated using Eq. (27):

$$\eta_{I,ECO} = (\dot{m}_{11} h_{11} - \dot{m}_{10} h_{10}) / (\dot{m}_6 h_6 - \dot{m}_7 h_7) \quad (27)$$

d) The energy efficiency of the chimney can be calculated using Eq. (28):

$$\eta_{I,CH} = (\dot{m}_8 h_8) / (\dot{m}_7 h_7) \quad (28)$$

e) The energy efficiency of the pump can be calculated using Eq. (29):

$$\eta_{1,P} = \dot{m}_9 (h_{10} - h_9) / W_P \quad (29)$$

f) The energy efficiency of the ventilation fan can be calculated using Eq. (30):

$$\eta_{1,VF} = \dot{m}_1 (h_1 - h_2) / W_{VF} \quad (30)$$

g) Energy efficiency of the overall system

Energy utilization factor (EUF) is used in the determination of the energy efficiency of cogeneration system and calculated using Eq. (31).

$$\eta_{I,system} = (W + Q)/\ \dot{m}_{ng} * LHV \tag{31}$$

The energy efficiency of the cogeneration system was accepted to be equal to the percentage of the energy provided to the system. W represents the power generation through turbine and Q represents the process heat. With respect to the input of the cogeneration system, it can be described as the supplied fuel energy. The rise in the energy of the feeding water and generated power can be defined as the product of cogeneration system.

3.2.4. Exergy Efficiencies

The energy efficiency analysis is not a promising approach to investigate the system performance due to the equivalence of heat and electricity. Therefore, compared with energy analysis, exergetic efficiency, similarly referred to as the 2nd law efficiency, affords a more accurate evaluation for the system performance. In the determination of the exergy efficiency of the system, the energy quality must be considered.

The exergy efficiency is the ratio of the exergy output to the exergy input. The common exergy efficiency can be defined with Eq. (32):

$$\eta_{II} = \text{exergy output / exergy input} = 1 - (\text{exergy loss / exergy input}) \tag{32}$$

a) Turbine

The exergy efficiency of the turbine can be found with Equ. (33)

$$\eta_{II,TE} = W_{TE}\ /\ (\dot{m}_4 ex_4 - \dot{m}_5 ex_5) \tag{33}$$

b) Boiler

To find the exergy efficiency of the boiler, the exergy transfer in the boiler through the heat exchangers is accepted to be the exergetic product and the difference between the exergy rate of the combustion gases is accepted to be exergetic fuel. Hence, the exergy efficiency of the boiler is calculated with Equ. (34):

$$\eta_{II,B} = (\dot{m}_{12} ex_{12} - \dot{m}_{11} ex_{11})\ /\ (\dot{m}_5 ex_5 - \dot{m}_6 ex_6) \tag{34}$$

c) The exergy efficiency of the economiser can be calculated with Eq. (35):

$\eta_{II,ECO} = (\dot{m}_{11}ex_{11} - \dot{m}_{10}ex_{10}) / (\dot{m}_6ex_6 - \dot{m}_7ex_7)$ (35)

d) The exergy efficiency of the chimney can be calculated with Eq. (36):

$\eta_{II,CH} = (\dot{m}_8ex_8) / \dot{m}_7ex_7$ (36)

e) Exergy efficiency for overall system

The exergy efficiency of the cogeneration system is accepted to be equal to percentage of the exergy provided to the system. Hence, the exergetic efficiency can be calculated with Eq. (37)

$\eta_{II,system} = W+E_Q / Ex_{ng}$ (37)

whereEx$_{ng}$ is the chemical exergy of natural gas.

3.2.5. Exergoeconomic Analysis

This study is carried out tomeet and develop the economic point of view for the cogeneration power plant using the actual operation data. The evaluation of exergetic performance for the components of cogeneration system and exergy-cost relations are done to show the relationship between thermodynamics and thermoeconomic evaluation of the cogeneration plants for food industry.The exergoeconomic analysis is done using SPECO method.

Specific Exergy Costing (SPECO) method, which defines the fuel and product of a components getting a regular record of all exergy supplements to and disposals from all the exergy streams of the system, and calculates the costs implementing main rules from business administration. (Lazzaretto and Tsatsaronis, 2006)

In a conventional economics analysis, for each control volume k, a cost equilibration is often derived for the total system operating under steady state conditions:

$\sum_{in} C_k + Z_k^T = \sum_{out} C_k + C_k^W + C_k^Q$ (38)

$C_k = c_k Ex_k$ (39)

$C_k^w = c_k W_k$ (40)

$$C_k^Q = c_k E_k^Q \quad (41)$$

$$Z_k^T = Z_k^{Cl} + Z_k^{OM} \quad (42)$$

where C_k, C_k^w, and C_k^Q represent the exergy costs of the streams, power, and heat, respectively; c represents the unit exergy costs of the streams, power, and heat; Ex_k, W_k, E_k^Q represent the exergy of the stream, power, heat ingoing and outgoing the control volume; Z_k^{Cl}, Z_k^{OM} and Z_k^T represent the leveled expenses for the capital investing by hours, operation and maintenance, and the over-all cost of the material within the control volume .

The hourly leveled cost method was employed to find Z_k^{Cl}.

The capital recovery factor (CRF):

$$CRF = \frac{i(i+1)^n}{i(i+1)^n - 1} \quad (43)$$

The cost rate of the sub-systems, CR_k:

$$CR_k = \frac{PEC_k}{\Sigma_{SYSTEM}\, PEC} \quad (44)$$

The hourly leveled capital investment cost of the kth component, Z_k^{Cl} :

$$Z_k^{Cl} = Z_{SYSTEM}^{Cl} CR_k \quad (45)$$

here, τ, i, j, n, and PEC represent the sum quantity of operating hours of the system under full load conditions, the interest rate, the recovery value ratio, the life time for the system, and the cost of equipment purchase. For the system, τ, i, j, and n were determined as 8200, 0.15, 0.12, and 15 years.

$$Z_k^{OM} = Z_k^{OCl} \phi \quad (46)$$

where the maintenance and operating costs are kept in view by taking the factor ϕ as 0.85 for the cogeneration power plant and its components:

Unit exergy cost of the fuel c_3^{ng},

$$c_3^{ng} = \frac{Pr^{ng}}{ERLHV10^{-6}(\frac{Gj}{kJ})} \quad (47)$$

where $\mathrm{Pr}^{\mathrm{ng}}$, LHV, and ER represent the selling value of the fuel in Turkish currency (₺), LHV of the natural gas, and exchange rate between ₺ and USD dollar.

The unit exergy cost of the electricity $\mathrm{c}_{21}^{\mathrm{W}} = \mathrm{c}_{22}^{\mathrm{W}} = \mathrm{c}_{23}^{\mathrm{W}}$,

$$\mathrm{c}^{\mathrm{W}} = \frac{\mathrm{Pr}^{\mathrm{W}}}{\mathrm{ER3600}(\frac{\mathrm{s}}{\mathrm{h}})10^{-6}(\frac{\mathrm{Gj}}{\mathrm{kJ}})} \tag{48}$$

here, Pr^{W} and ER represent the selling price of electricity in ₺and the exchange rate between ₺ and USD, respectively.

$C_{D,k}$ represents the expense rate of the exergy destruction and revealed how many dollars per an hour (US Dollar/h) are destructed during the process of the unit and given by Eq. (49):

$$C_{D,k} = c_{F,k}Ex_{D,k} \tag{49}$$

The origins of the cost of a component can be divided into two groups: 1) non-exergy related costs (capital investments, operating and maintenance expenses) and 2) exergy destructıon and exergy loss. Exergoeconomic factor, f_k, can be used in evaluation of the performance of a component to derive information about the related significance of each group and is defined by Eq. (50):

$$\mathrm{f}_{\mathrm{k}} = \frac{\mathrm{Z}_{\mathrm{k}}^{\mathrm{T}}}{\mathrm{Z}_{\mathrm{k}}^{\mathrm{T}}+\mathrm{c}_{\mathrm{F,k}}(\mathrm{Ex}_{\mathrm{D,k}}+\mathrm{Ex}_{\mathrm{L,k}})} \tag{50}$$

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Thermodynamic Analysis Findings

In the study, the thermodynamic analysis of a cogeneration system was done using the 1st and 2nd law of thermodynamic to find the efficiency of the system. Furthermore, the influence of steam pressure on energy and exergy efficiencies of the boiler was investigated. Table 4.1. shows the fluid types, temperatures, pressures, mass flow rates, and exergy rates for the cogeneration plant in terms of their state numbers.

Table 4.1. The exergy rate and other properties (for state no, please refer to Figure 3.1) (Ozdil and Pekdur 2016)

State no	Fluid Type	Mass flow rate (kg/s)	Temperature (K)	Pressure (kPa)	$\dot{E}x$ (kW)
1	Air	15.486	303	101.325	9.933
2	Air	15.486	295	101.325	0.135
3	Natural gas	0.518	288	2600	2,723,282.626
4	Comb. gas	40.213	1033	1700	49,524.458
5	Comb. gas	40.213	763	1700	42,201.988
6	Comb. gas	40.213	533	1700	36,473.211
7	Comb. gas	40.213	459	1700	34,793.617
8	Comb. gas	40.213	403	1700	33,596.101
9	Water	6.11	377	1900	238.952
10	Water	6.11	378	1900	245.196
11	Water	6.11	453	1900	798.481
12	Steam	6.11	463	1200	5173.192
Boiler	Ex_{LOSS}	-	-	-	578.954
ECO	Ex_{LOSS}	-	-	-	404.105
CH	Ex_{LOSS}	-	-	-	669.204

Figure 4.1., 4.2., 4.3., and 4.4. demonstrate the exergy destruction, energy and exergy efficacies of the main units, and distribution of exergy destruction, respectively. Table 4.2. shows the exergy destructions and energy and exergy efficiencies computed with the above equations. As given the table, the energy efficiencies of the CH, ECO, and boiler are approximately 63.99%, 66.03%, and 79.91%, respectively, while the exergy efficiencies of the CH, ECO, and boiler are 96.55%, 32.94%, and 76.36%, respectively. As revealed by Figure 4.2., the energy efficiencies of the majority of the components are above 0.6. The major sources of the inefficiency in the system are listed below.

i. The value of the excessive air supply to system significantly affected the efficiency of the system. The mass flowing rate of the combustion gas increased with raising amounts of excess air. The increase in the mass flow rate of the combustion leads to decreased component temperatures and increased heat loss in system, hence, the efficiency of system declines.

ii. Chemical reaction in the combustion procedure can lead to rise in the system irreversibility. The results obtained in the study indicated that, although there is an opportunity for improvement through the reduction of the level of excess air, the cogeneration system had satisfactory combustion efficiency when the composition of the combustion gas obtained from the chimney is considered.

iii. The highest irreversibility was determined in the boiler, which was attributed to the low level of heat transfer from the combustion gas to water by means of heat exchangers. The steam is among the system outputs and its pressure and temperature affect the boiler performance significantly. Thus, increasing the pressure and temperature of the steam may prove beneficial in increasing the heat transfer to the water, which, in turn, will increase the powers of the boiler output and overall system output. The system performance can be optimized and enhanced by increasing heat transfer to water, which results in the effective arrangement of the heat exchangers both in the boiler and ECO and help select better materials. The ECO had the second highest irreversibility after the boiler. The irreversibility of the boiler can be reduced by reducing the temperature of the combustion gas obtained from turbine. The temperature of the boiler output declines with decreasing combustion gas temperature and thus, the irreversibility of the ECO is reduced. A better insulation can also contribute to the decrease in the irreversibility of the ECO.

iv. The fuel type is also of importance in the efficiency of the overall system, since the calorie finding representing internal energy of fuel directly affects the efficiency of the system.

Table 4.2. The exergy destruction and energy and exergy efficiency values of components in the cogeneration system (Ozdil and Pekdur 2016)

Components	$\dot{E}x_D$(kW)	η_I(%)	η_{II}(%)
Boiler	775.11	79.91	76.36
ECO	722.20	66.03	32.94
CH	528.31	63.99	96.55
Turbine	0	100	58.58
Pump	64.80	31.65	7.52
Ventilation Fan	39.28	24.10	32.66

The steam pressure was increased by 1 bar until it reached 13 bar from 6 bar to investigate how the efficiency of the system is affected by steam pressure. Given in Figure 4.5., as the steam pressure increases, the internal energy of the steam goes up so that the power output increases. When the steam pressure is increased from 6 bar to 13 bar as shown in Table. 4.3,

i. 1.5% rise in the energy efficiency of the boiler was obtained.
ii. 9.25% rise in the exergy efficiency of the boilerwas obtained.

Hence, conclusively, increasing the steam pressure at boiler output positively affected efficiencies of boiler and system.

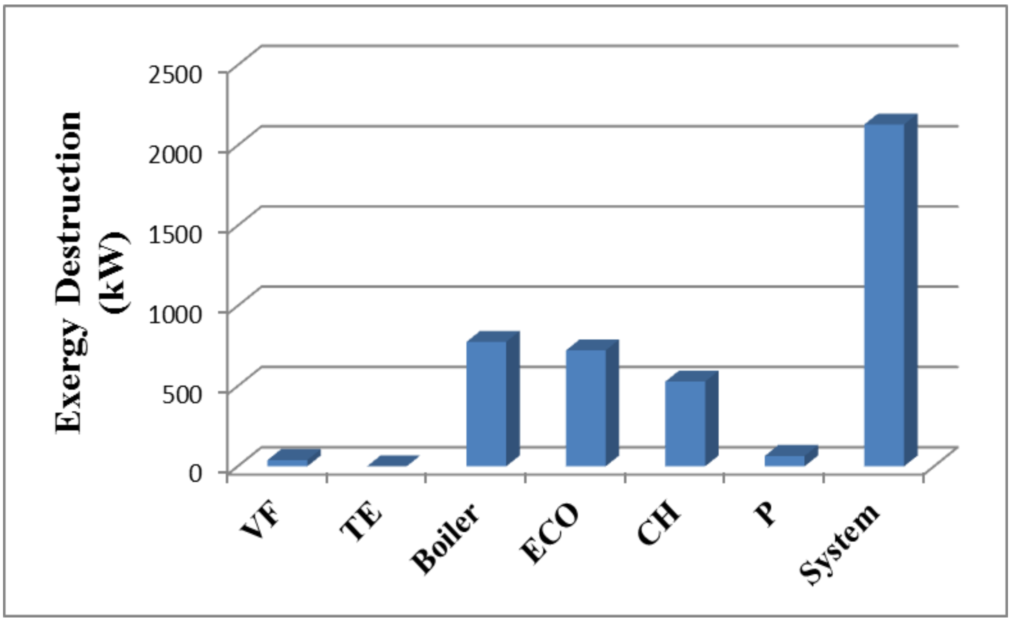

Figure 4.1. Exergy destruction in the components of the cogeneration system (Ozdil and Pekdur 2016)

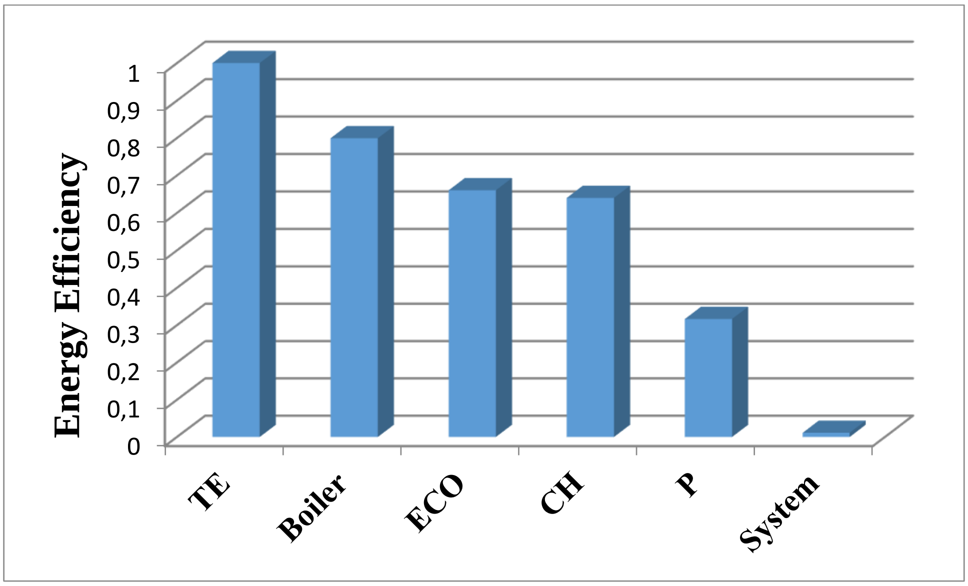

Figure 4.2. Energy efficiency of the main components of the cogeneration system (Ozdil and Pekdur 2016)

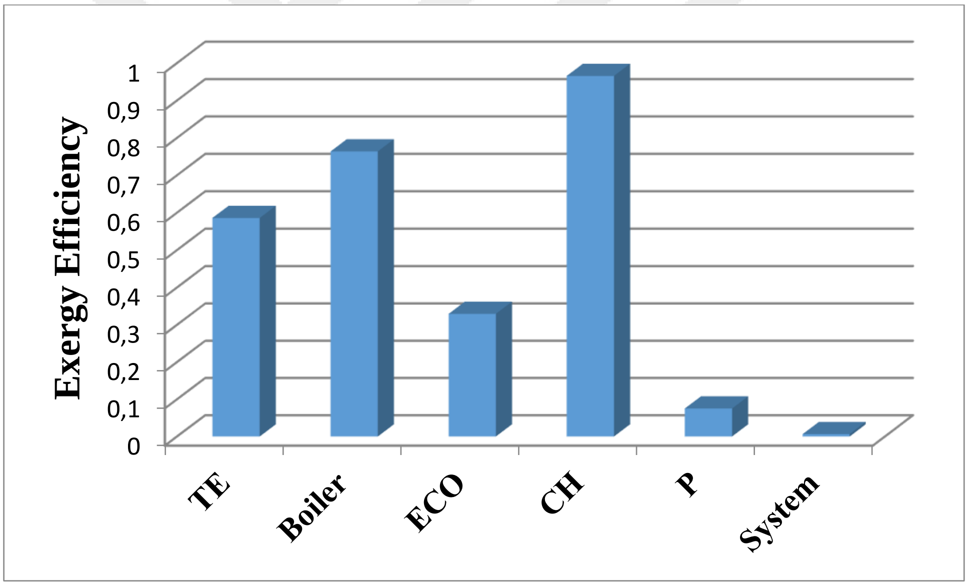

Figure 4.3. Exergy efficiency of the main components of the cogeneration system (Ozdil and Pekdur 2016)

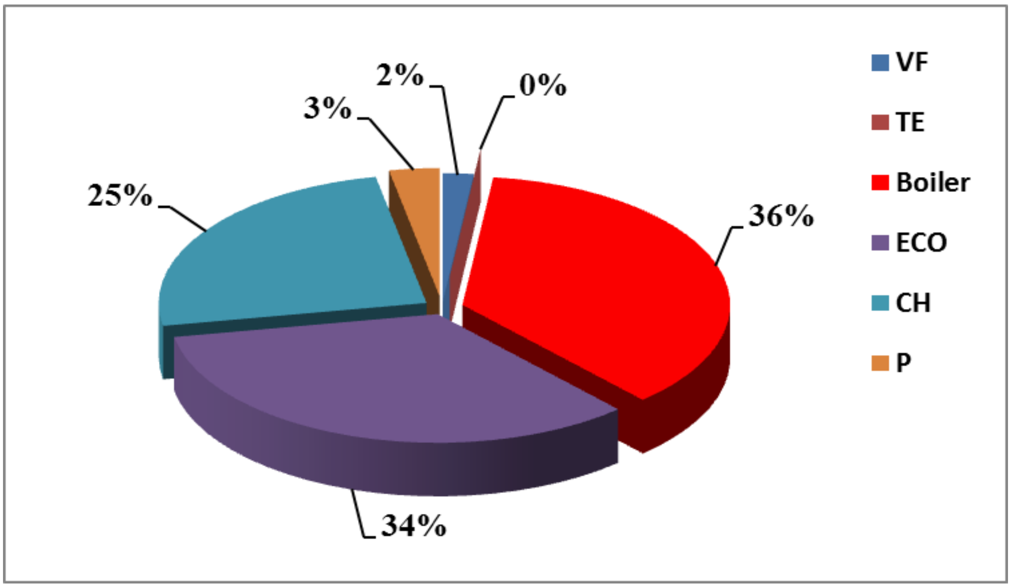

Figure 4.4. Distribution of the exergy destruction rates of the components of the cogeneration system (Ozdil and Pekdur 2016)

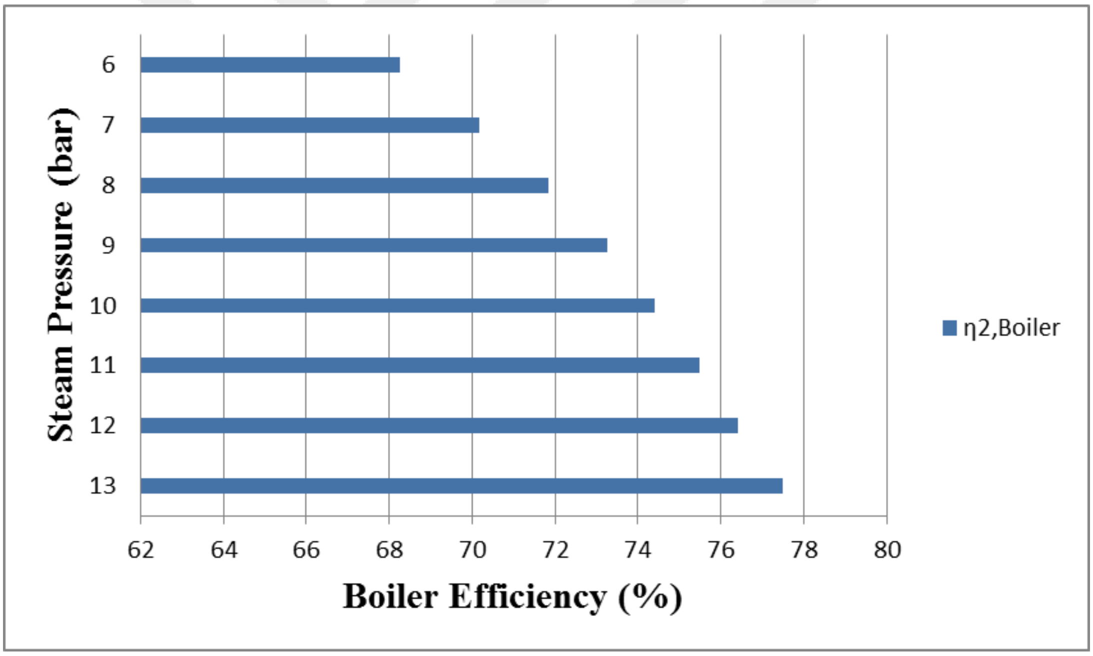

Figure 4.5. The impact of steam pressure on the exergy efficiency of the boiler (Ozdil and Pekdur 2016)

Table 4.3. The impact of the steam pressure on the energy and exergy efficiency of boiler at 6 bar and 13 bar (Ozdil and Pekdur 2016)

	Pressure (bar)		Total
	6	13	Changes (%)
$\eta_{I\ (\%)}$	78.41	79.91	1.5
$\eta_{II\ (\%)}$	68.25	77.50	9.5

4.2. Exergoeconomic Analysis Results

The investigation of exergoeconomic performance is put forth to Show the relationship between thermodynamics and economic evaluation with respect to the use of thermodynamic laws and exergoeconomic equations. Table 4.4 shows the total costs, purchased equipment costs, hourly leveled capital investing costs, and operating and maintenance costs of equipment and overall system. Figures 4.6., 4.7., and 4.8 shows the cost rates, purchased equipment costs, and total investment costs of the equipment, respectively. As revealed by the figures, the CPP equipment had the highest value. Table 4.5. shows the unit exergy cost and exergy expenses of equipment in CPP.

Given in Table 4.5., the unit exergy expense and exergy expense of the fuel were 0.05 US Dollar/GJ and 490.23US Dollar/h. According to results given in Table 4.4, the operation and maintenance cost, capital investment cost, and total cost of the system were found as 231.66, 218.55, and 450.21 US dollar/hour.

Table 4.4. The distribution of the cost rate, cost of the bought equipment, the leveled capital investing, the costs of operation and maintenance, and total expenses by material (Ozdil and Pekdur 2016)

COMPONENTS	CR_k	PEC[US Dollar]	Z_k^{CI}[US Dollar/h]	Z_k^{OM} [US Dollar/h]	Z_k^{T}[US Dollar/h]
Ventilating Fan (VF)	0.03	236.207	7.54	7.99	15.52
Turbine	0.23	1.574.713	50.24	53.26	103.50
Boiler	0.46	3.149.425	100.48	106.51	206.99
Economizer (ECO)	0.16	1.102.299	35.17	37.28	72.45
Chimney (CH)	0.08	551.149	17.58	18.64	36.22
Pump (P)	0.03	236.207	7.54	7.99	15.52
TOTAL	1.00	6.850.000	218.55	231.66	450.21

Table 4.5. The distribution of the rate of exergy, cost of unit exergy and cost of exergy (Ozdil and Pekdur 2016)

State No.	Ex [GJ/hour]	c [US Dollar/GJ]	C [US Dollar/hour]
1	0.04	0.00	0.00
2	0.00	39028.17	19.02
3	9803.82	0.05	490.23
4	178.29		509.25
5	151.93	0.05	7.60
6	131.30	0.05	6.57
7	125.26	0.05	6.26
8	120.95	0.35	42.39
9	0.86	0.00	0.00
10	0.88	24.11	21.29
11	2.87	32.67	93.91
12	18.62	16.20	301.79
VF - 13	0.14	24.69	3.49
Turb. - 14	0.37	1618.51	605.15
Boiler - 15	2.79	0.05	0.14
ECO - 16	2.60	0.05	0.13
CH - 17	1.90	0.05	0.10
Pump - 18	0.23	24.69	5.76

In figure 4.9, cost rates of exergydestruction for whole equipment are demonstrated whilst the uttermost cost rate of exergydestruction is obtained in CPP equipment. The factors of exergoeconomic for whole equipment are exhibited in figure 4.10. The most important reason of the highest exergoeconomic factor in the pump is that the initial investment cost and exergy destruction at it is too low compared to other equipment. But, because of considerably upper value of exergy destruction, lowest exergoeconomic factor is obtained in CPP.

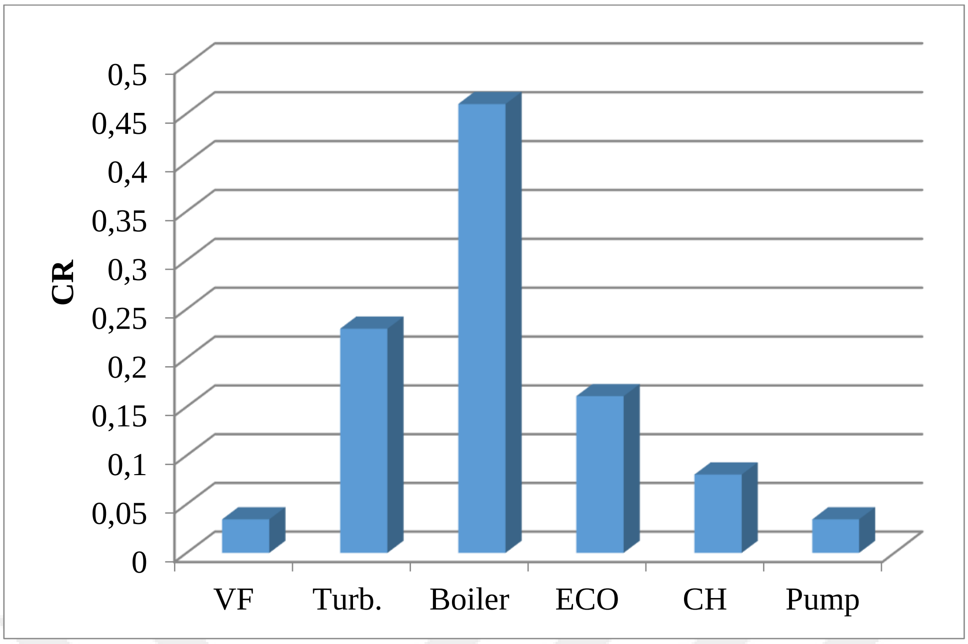

Figure 4.6. The costs of the components of the CPP

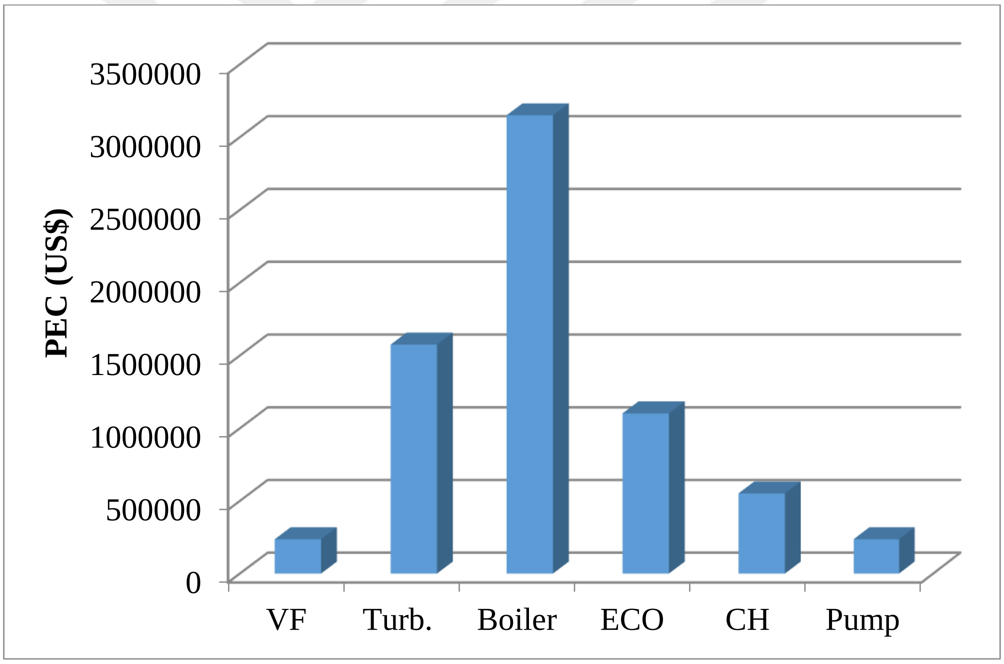

Figure 4.7. The costs of thepurchased equipment for the components of the CPP

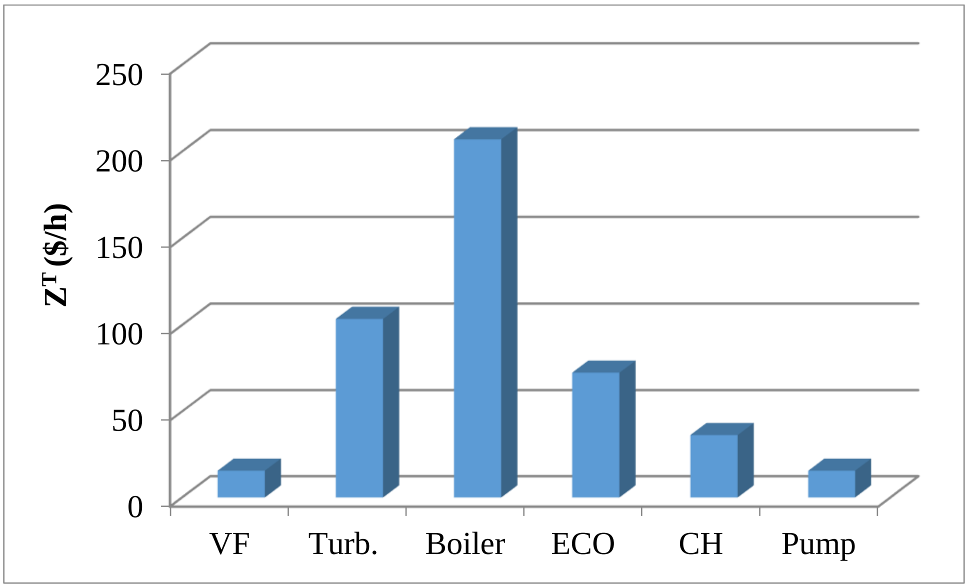

Figure. 4.8. Total investment costs of the components of the CPP

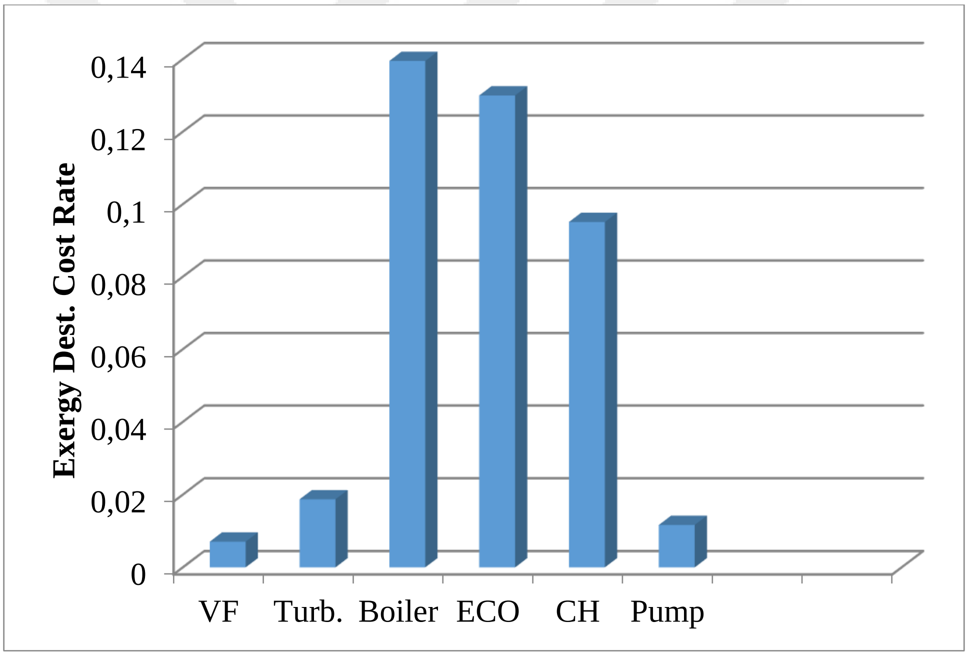

Figure. 4.9. Exergy destruction expense rates of components of the CPP

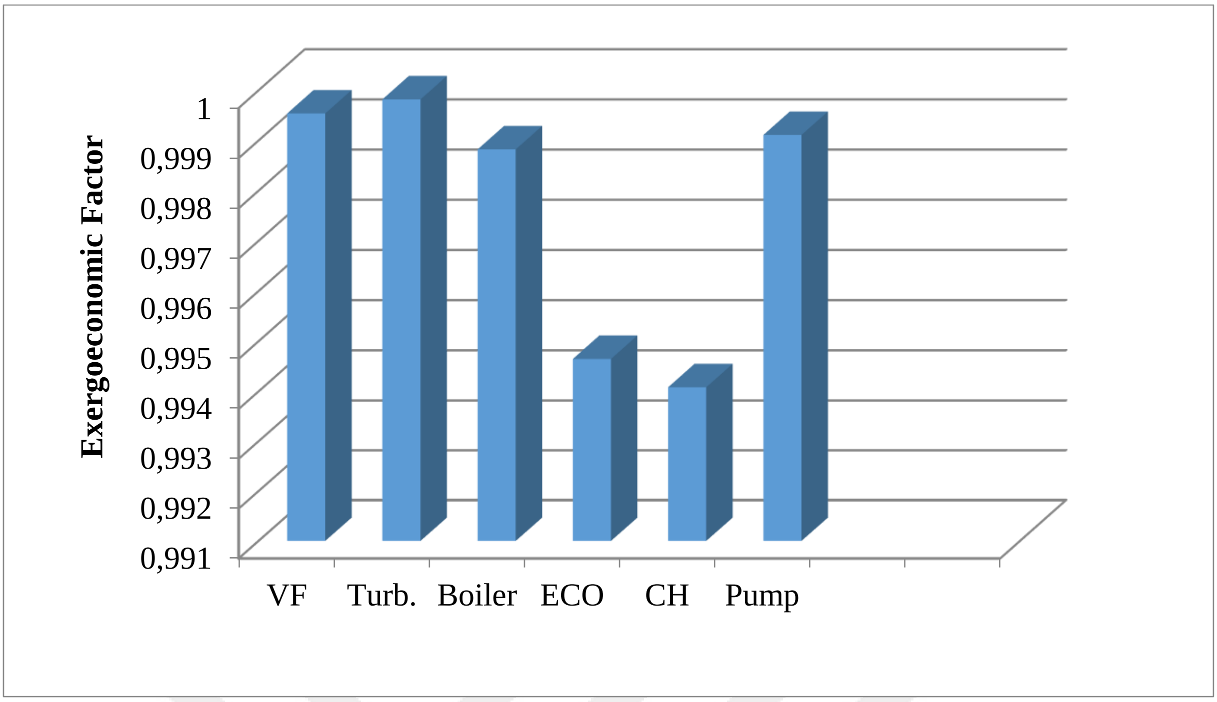

Figure 4.10. Exergoeconomic factors of the components of the CPP

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CHAPTER 5: CONCLUSION

In the study, the 1st and 2nd laws of thermodynamic were applied to an actual cogeneration power plant and the energy and exergy analyses were carried out. The findings showed that greatest exergy destruction was around 775.111 kW and had occurred in the boiler, which was attributed to the large value of excessive air directly affecting the combustion gas flow rate. The heat losses in the boiler increase with increasing amounts of excess air due to the decreasing boiler temperature. Furthermore, the steam pressure is a further important parameter for the system efficiency as it stimulates the exergy output positively. Increasing steam pressure, for instance, has positive influence on the system efficiency.

We can list the recommendation to improve the system performance as below:

i. The quantity of the supplied excess air to the system has significant effect on the system efficiency. The increase in the excess air leads to increase of the mass flow rate of the combustion gas. Due to the increase in the mass flow rate of the combustion gas, the boiler temperature decreases and the heat losses in the system increase; after that, the efficiency of the system decreases.

ii. The chemical reaction in the combustion process can give rise to the larger system irreversibility. In this study, composition of the combustion gas gained from the chimney points that the cogeneration system has satisfactory combustion efficiency, but it can be developed in decrement of the excess air amount.

iii. The boiler has the largest irreversibility owing to the poor heat transfer from the combustion gas to the water via the heat exchangers. One of the system outlets is the steam and its pressure and temperature are influential factors on the boiler efficiency. Increasing the steam pressure and temperature results in higher heat transfer to the water, so that the power of the boiler output and overall system output increases.

iv. The system performance can be optimized and developed by increasing the heat transfer to the water which results in effective arrangement of the heat exchanger located in both the boiler and ECO and also better material selection. ECO has the second biggest irreversibility thereafter the boiler. What is more, the irreversibility of the boiler can be diminished by decreasing the temperature of the combustion gas obtained from the turbine. By virtue of the decline in the temperature of the combustion gas, the temperature at the boiler outlet also diminishes and in this manner, irreversibility of the ECO dwindles. The irreversibility of the ECO can also be diminished with effective insulation.

v. The type of the fuel is a further important factor for the efficiency of the overall system as the calorific value representing internal energy of the fuel affects directly the system efficiency.

vi. All of the exergoeconomic factors, belonging the components of the system, are obtained higher than 0.99. When we consider the exergoeconomic factor, which is an important parameter for exergoeconomic analysis, it has been observed that in general all equipment have high values. High exergoeconomic factor results refer to that all monetary costs of the system are happened due to investment cost, operational and maintenance costs. For this reason, trying to increase the exergoeconomic effectiveness of the system will not be very realistic. Because increment of the system efficiency will not affect the monetary costs of the system. If the obtained exergoeconomic factor value is low, the system efficiency can be improved.

REFERENCES

Anonymous. 2017. http://www.megenergy.com/operations/cogeneration Access Date: 26.02.2018

Anonymous. 2017. http://emhk.itu.edu.tr/yuksek-verim-ve-temiz-enerji-kojenerasyon-sistemleri/ Access Date: 26.02.2018

Anonymous. 2010. https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/cogeneration-plant-chp-combined-heat-and-power Access Date: 26.02.2018

Anonymous. 2017. http://www.enerji.gov.tr/tr-TR/Sayfalar/Elektrik Access Date: 26.02.2018

Abusoglu A, Kanoglu M. 2009. Exergetic and thermoeconomic analyses of diesel engine powered cogeneration: Part 1 – Formulations. Applied Thermal Engineering, 29: 234–241.

Bade, MH, Bandyopadhyay S. 2015. Analysis of gas turbine integrated cogeneration plant: Process integration approach. Applied Thermal Engineering 78: 118-128.

Bonnet S, Alaphilippe M, Stouffs P. 2005. Energy, exergy and cost analysis of a micro-cogeneration system based on an Ericsson engine. International Journal of Thermal Sciences, 44: 1161–1168.

Can OF, Celik N, Dagtekin I. 2009. Energetic–exergetic-economic analyses of a cogeneration thermic power plant in Turkey. International Communications in Heat and Mass Transfer, 36: 1044–1049.

Gholamian E, Mahmoudi SMS, Zare V. 2016. Proposal, exergy analysis and optimization of a new biomass-based cogeneration system. Applied Thermal Engineering, 93: 223–235.

Gurturk M, Oztop HF. 2010. Exergy analysis of a circulating fluidized bed boiler cogeneration power plant. Energy Conversion and Management, 120: 346–357.

Kamate SC, Gangavati PB. 2010. Exergy analysis of cogeneration power plants in sugar industries. Applied Thermal Engineering, 29: 1187–1194.

Kim SM, Oh SD, Kwon YH, Kwak HY 1998. Exergoeconomıc Analysıs Of Thermal Systems. Energy, Vol. 23, No. 5, pp. 393–406.

Kumar R. 2017. A critical review on energy, exergy, exergoeconomic and economic (4-E) analysis of thermal power plants. Engineering Science and Technology, an International Journal, 20: 283–292.

Lazzaretto A, Tsatsaronis G. 2006. SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems, Energy, 31(8): 1257-1289.

Lee JH, Kim TS, Kim E 2017. Prediction of power generation capacity of a gas turbine combined cycle cogeneration plant. Energy, 124: 187e197

Mert MS, Dilmaç ÖF, Özkan S, Karaca F, Bolat E. 2012. Exergoeconomic analysis of a cogeneration plant in an iron and steel factory. Energy, 46: 78e84

Nemati A, Nami H, Ranjbar F, Yari M. 2017. A comparative thermodynamic analysis of ORC and Kalina cycles for waste heat recovery: A case study for CGAM cogeneration system. Case Studies in Thermal Engineering, 9 : 1–13.

Orhan MF, Dincer I, Rosen MA. 2009. Energy and exergy analyses of the fluidized bed of a copper–chlorine cycle for nuclear-based hydrogen production via thermochemical water decomposition. Chemical Engineering Research and Design, 87: 684–694.

Ozdemir K, Hepbasli A, Eskin N. 2010. Exergoeconomic analysis of a fluidized-bed coal combustor (FBCC) steam powerplant. Applied Thermal Engineering, 30: 1621-1631.

Ozdil NFT, Tantekin A. 2016. Exergy and exergoeconomic assessments of an electricity production system in a running wastewater treatment plant. Renewable Energy, 97: 390-398.

Ozdil NFT, Pekdur A. 2016. Energy and exergy assessment of a cogeneration system in food industry: a case study. International Journal of Exergy, Vol. 20, No. 2, pp. 254-268

Ozdil NFT, Tantekin A. 2017. Exergoeconomic analysis of a fluidized bed coal combustion steam power plant. Thermal Scıence, Vol. 21, No. 5, pp. 1975-1984.

Puadian N, Li J, Pang S. 2014. Analysis of Operation Parameters in a Dual Fluidized Bed Biomass Gasifier Integrated with a Biomass Rotary Dryer: Development and Application of a System Model. Energies, 7: 4342-4363; doi:10.3390/en7074342.

Santos AC, Puch GZ, Diez DB, Dieguez CG. 2016. Thermodynamic and exergoeconomic analysis of energy recovery system of biogas from a wastewater treatment plant and use in a Stirling engine. Renewable Energy, 88: 171-184.

Silveira JL, Beyene A, Leal EM, Santana JA, Okada D. 2002. Thermoeconomic analysis of a cogeneration system of a university campus. Applied Thermal Engineering, 22: 1471–1483

Uysal C, Kurt H, Kwak HY. 2017. Exergetic and thermoeconomic analyses of a coal-fired power plant. International Journal of Thermal Sciences, 117: 106-120

Wu Y, Yang W, Blasiak W. 2014. Energy and Exergy Analysis of High Temperature Agent Gasification of Biomass. Energies, 7: 2107-2122; doi:10.3390/en7042107.

Yildirim U, Gungor A. 2012. An application of exergoeconomic analysis for a CHP system. Electrical Power and Energy Systems, 42: 250–256.

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