REPUBLIC OF TURKEY
UŞAK UNIVERSITY
GRADUATE EDUCATION INSTITUTE

DEPARTMENT OF MECHANICAL ENGINEERING

ENHANCED THERMODYNAMIC ANALYSIS AND ASSESSMENT OF A COGENERATION SYSTEM FOR A CERAMIC FACTORY

DOCTORAL DISSERTATION

HASAN ÇAĞLAYAN

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UŞAK

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DOCTORAL DISSERTATION DECLARATION

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Hasan ÇAĞLAYAN

SERAMİK FABRİKASI İÇİN KOJENERASYON SİSTEMİNİN GENİŞLETİLMİŞ TERMODİNAMİK ANALİZİ VE DEĞERLENDİRMESİ

(DOKTORA TEZİ)

HASAN ÇAĞLAYAN

UŞAK ÜNİVERSİTESİ
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ÖZET

Kurutma, pişirme, ısıtma gibi enerji yoğun proseslere sahip olan seramik sektöründe, enerji maliyeti, toplam üretim maliyetinin %35’in üzerine çıkabilmektedir. Özellikle doğalgaz, petrol gibi yakıtların tamamına yakınının ülkemize ithal edilmesine bağlı olarak artan enerji maliyetleriyle birlikte ülkedeki şirketlerin küresel piyasalarda rekabet etme gücü azalmaktadır. Ayrıca bu prosesler de kullanılan inorganik hammadde ve tüketilen doğalgazın, çevreye olan etkileri her geçen gün artmaktadır. Genel olarak bu endüstride etkin bir enerji etüt çalışmaları yapılmadığı için verimsizliğe yol açan komponentlerin tespit edilemediği gözlenir. Böylesi bir maliyet ve çevresel etkiyle karşı karşıya kalan şirket yöneticileri, fabrikaları bir bütün olarak değerlendirdikleri için, komponent bazında tersinmezlikleri göz ardı etmektedirler. Günümüzde, özellikle kurutma proseslerine sahip olan seramik sektörü için çeşitli enerji geri kazanım sistemleri uygulanmaktadır. Fakat bunların içerisinde gaz türbinli kojenerasyon sisteminin uygulanması hakkında termodinamiksel ve ekonomik açıdan hala kesin bir yargıya varılmış değildir.

Bu tezde, Uşak Organize Sanayi Bölgesinde yer alan bir seramik fabrikası için modellenen kojenerasyon sisteminin ekserji, eksergoekonomik ve ekserjoçevresel analizlerinin yanında, ileri ekserji, ileri eksergoekonomik ve ileri çevresel analizlerinin uygulaması, beş farklı ölü durum sıcaklığı için gerçekleştirilmiştir. Ayrıca, yatırımı yapılacak olan kojenerasyon sistemi için “Net Şimdiki Değer” yöntemi kullanılarak, karlılık analizi yapılmış ve yatırımın başabaş noktası tespit edilmiştir.

Geleneksel ekserji, eksergoekonomik ve eksergoçevresel analizine göre, komponentler arasında sırasıyla en yüksek ekserji yıkım, ekserji maliyet oranı ve eksergetik çevresel etki oranına sahip olan yanma odasının iyileştirme potansiyeli, diğer komponentlere göre daha yüksek olduğu kabul edilir. Fakat ileri ekserji, eksergoekonomik ve eksergoçevresel analizine göre, duvar karosu ve yer karosu kurutucuların kaçınılabilir ekserji yıkım değeri, ekserji yıkım maliyet oranı ve çevresel etki oranı, diğer komponentlerden daha yüksek bulunmuştur. Bu yüzden duvar ve yer karosu kurutucularının iyileştirme potansiyeli her üç analizde de yanma odasından daha fazla olduğu söylenebilir. Ayrıca duvar ve yer karosu kurutucuların üzerine daha çok odaklanılması gerektiği anlaşılır. Bunun yanında kojenerasyon sisteminin toplam ekserji yıkım değerinin %90’nından, toplam ekserji yıkım maliyet oranının %96’sından ve toplam çevresel etki oranının %96’sından fazlası komponentlerde meydana gelen tersinmezliklerden kaynaklanmaktadır. Bu yüzden komponentler arasındaki etkileşimin ekserjetik, ekonomik ve çevresel açıdan zayıf olduğu söylenebilir. Net şimdiki değer yöntemine göre gaz türbinli kojenerasyon sistemi, 13. yılında başa baş noktasına ulaşırken, yaşam ömrü boyunca sağladığı toplam kazanç 562148$’dır.

Bilim Kodu : 625.04.01
Anahtar Kelimeler : Seramik fabrikası, kojenerasyon, gaz turbine, ekserji analizi, eksergoekonomik, eksergoçevresel, ileri ekserji analizi, ileri eksergoekonomik analizi, ileri eksergoçevresel analizi, net şimdiki değer
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SUMMARY

In the ceramic industry, which has energy-intensive processes such as drying, firing, heating, the energy cost can exceed 35% of the total production cost. Especially with rising energy costs due to the import of almost all fuels such as natural gas and petroleum, the power of companies in the country to compete in global markets is decreasing. In addition, the effects of inorganic raw materials used in these processes and natural gas consumed on the environment are increasing every day. In general, it is observed that the components that lead to inefficiency cannot be detected because energy studies are not carried out effectively in this industry. Faced with such a cost and environmental impact, company executives ignore component irreversibilities, as they evaluate industry as a whole. Today, various energy recovery systems are applied, especially for the ceramic industry, which has drying processes. However, there is still no conclusive decision regarding the implementation of the gas turbine cogeneration system thermodynamically and economically.

In this thesis, besides the exergy, exergoeconomic and exergoeconomic analysis of the cogeneration system modeled for a ceramic factory located in Uşak Organized Industrial Zone, the application of advanced exergy, advanced exergoeconomic and advanced environmental analysis is carried out for five different dead state temperatures. In addition, using the “Net Present Value” method for the cogeneration system to be invested, profitability analysis is made and the breakeven point of the investment is determined. According to conventional exergy, exergoeconomic and exergoeconomic analysis, the improvement potential of the combustion chamber, which has the highest exergy destruction, exergy cost rate and exergetic environmental impact rate among components, respectively, is considered to be higher than other components. However, according to advanced exergy, exergoeconomic and exergoeconomic analysis, the avoidable exergy destruction value, avoidable exergy destruction cost rate and avoidable environmental impact rate of wall tile and ground tile dryers are found to be higher than other components. Therefore, the improvement potential of wall and floor tile dryers can be said to be higher than that of the combustion chamber in all three analyses. It is also understood that more focus should be placed on wall and floor tile dryers. In addition, more than 90% of the total exergy destruction value of the cogeneration system, more than 96% of the total exergy destruction cost rate and more than 96% of the total environmental impact rate are due to irreversibilities occurring in the components themselves. Therefore, it can be said that the interaction between the components is exergetic, economical and environmentally weak. According to the Net Current Value method, the gas turbine cogeneration system reaches breakeven point in 13 years, while the total gain it provides over its life time is $562148.

Science Code **:** 625.04.01

Keywords **:** Ceramic plant, cogeneration, gas turbine, exergy analysis, exergoeconomic, exergoenvironmental, advanced exergy analysis, advanced exergoeconomic analysis, advanced exergoenvironmental, net present value

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HASAN ÇAĞLAYAN

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NOMENCLATURE

Some of the “Symbols”, “Abbreviations”, “Subscripts” and “Greek letters” used in this study are shown below, respectively:

Symbols	**Explanation**
$\boldsymbol{A_t}$	Benefit per year ($/year)
$\boldsymbol{b}$	Specific environmental impact rate (Pts/h)
$\dot{\boldsymbol{B}}$	Environmental impact rate (Pts/h)
$\boldsymbol{B_t}$	Expenditure per year ($/year).
$\boldsymbol{c}$	Cost per unit of exergy ($/GJ)
$\dot{\boldsymbol{C}}$	Cost rate associated with exergy ($/h)
$\boldsymbol{c_p}$	Specific heat capacity at constant pressure (kJ/kg K)
$\dot{\boldsymbol{C}}\dot{\boldsymbol{A}}$	Annual capital cost ($/year)
$\bar{\boldsymbol{e}}_{\boldsymbol{k}}^{\boldsymbol{0}}$	Specific molar chemical exergy (kJ/kmol)
$\boldsymbol{E}$	Energy (kJ)
$\dot{\boldsymbol{E}}\boldsymbol{x}$	Exergy flow rate (kW)
$\dot{\boldsymbol{E}}\boldsymbol{x}\dot{\boldsymbol{I}}\boldsymbol{P}_{\boldsymbol{k}}$	Exergy improvement potential (kW)
$\boldsymbol{f}$	Exergoeconomic factor
$\boldsymbol{f_b}$	Exergoenvironmental factor
$\boldsymbol{g}$	Acceleration of gravity (m/s^2)
$\bar{\boldsymbol{g}}_{\boldsymbol{i}}$	Molar gibbs function
$\boldsymbol{h}$	Enthalpy (kJ/kg)

$\boldsymbol{K}$	Cost ($)
$\boldsymbol{KE}$	Kinetic energy (kJ)
$\dot{\boldsymbol{L}}$	Exergy consumption rate (kW)
$\dot{\boldsymbol{m}}$	Mass flow rate (kg/s)
$\boldsymbol{n}$	Number of period
$\boldsymbol{r}$	Relative cost difference specific environmental cost rate
$\boldsymbol{r_b}$	Relative difference of specific environmental impact rate
$\boldsymbol{P}$	Pressure (bar)
$\boldsymbol{PE}$	Potential energy (kJ)
$\boldsymbol{Q}$	Heat (kJ)
$\boldsymbol{R_t}$	Cash flow in year ($)
$\boldsymbol{R}$	Universal gas constant. (kJ/kg K)
$\overline{\boldsymbol{R}}$	Universal gas constant. (kJ/kmol K)
$\dot{\boldsymbol{R}}$	Exergoeconomic cost parameter
$\boldsymbol{s}$	Specific entropy (kJ/kg K)
$\dot{\boldsymbol{S}}$	Salvage value
$\boldsymbol{SI}$	Sustainability index
$\boldsymbol{T}$	Temperature (K)
$\boldsymbol{V}$	Velocity (m/s)
$\boldsymbol{v}$	Specific volume (m^3/kg)
$\dot{\boldsymbol{W}}$	Work rate (kW)
$\boldsymbol{x'}$	Mole rate
$\dot{\boldsymbol{Z}}$	Capital investment cost flow rate ($/h)

Abbreviations	**Explanation**
AC	Air Compressor
CC	Combustion Chamber
GT	Gas Turbine
PL	Pipe Line
WD	Wall Tile Dryer
GD	Ground Tile Dryer
COGEN	Cogeneration System
EXCEM	Exergy, Cost, Energy and Mass
LCA	Life Cycle Assessment
LHV	Lower Heating Value
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
PWF	Present Worth Factor
PEC	Purchased Equipment Cost
SPECO	Specific Exergy Costing
TL	Turkish Lira
TEP	Tons of Equivalent Oil

Subscripts	**Explanation**
0	Standard environmental state (dead state)
acc	Accumulate
AV	Avoidable

$\boldsymbol{ch}$	Chemical
$\boldsymbol{CI}$	Investment cost ($)
$\boldsymbol{CO}$	Manufacturing, transport and installation
$\boldsymbol{D}$	Destruction
$\boldsymbol{DI}$	Disposal
$\boldsymbol{en}$	Energy
$\boldsymbol{EN}$	Endogenous
$\boldsymbol{ex}$	Exergy
$\boldsymbol{EX}$	Exogenous
$\boldsymbol{func}$	Functional
$\boldsymbol{F}$	Fuel
$\boldsymbol{i}$	Current state
$\boldsymbol{in}$	Inlet
$\boldsymbol{k}$	*k*th component
$\boldsymbol{loss}$	Losses
$\boldsymbol{out}$	Outlet
$\boldsymbol{OM}$	Operation and maintenance
$\boldsymbol{ph}$	Potential
$\boldsymbol{P}$	Product
$\boldsymbol{q}$	Heat
$\boldsymbol{UN}$	Unavoidable
$\boldsymbol{x'}$	Mole rate
$\boldsymbol{w}$	Work

Greek letters	**Explanation**
$\boldsymbol{\psi}$	Exergy efficiency
$\boldsymbol{\gamma}$	Exergy coefficient of the specific exergy ratio
$\boldsymbol{\phi}$	Relative exergy consumption rate
$\boldsymbol{\mu}$	Salvage value percentage
$\boldsymbol{\Omega}$	Operation and maintenance factor
$\boldsymbol{\tau}$	Annual working hour
$\boldsymbol{\varepsilon_{mod}}$	Modified exergy efficiency

1. INTRODUCTION

As the need for energy resources in the world increases in all areas, this need increases enormously in the industrial sector due to the high economic growth rates of countries. In the globalizing world, competition conditions and negative environmental conditions are becoming more severe, while the reduction of fossil fuel sources is highlighting the effective use of energy. In particular, the energy consumption of industrial sectors such as refining, mining, manufacturing, agriculture, and construction accounts for more than 50% of the total energy consumption. This figure is expected to increase by 30% from 2018 to 2050 and reach 92.317 ZW. While the annual energy consumption in the Organisation for Economic Co-operation and Development (OECD) countries of which Turkey is a member has increased by 0.5%, the energy consumption of non-OECD countries has increased by around 1%. The energy consumption in the industrial sector of OECD and non-OECD countries increased by 1.4% annually between 2006 and 2030, a total increase of 33% can be seen in Figure 1.1 [1-3].

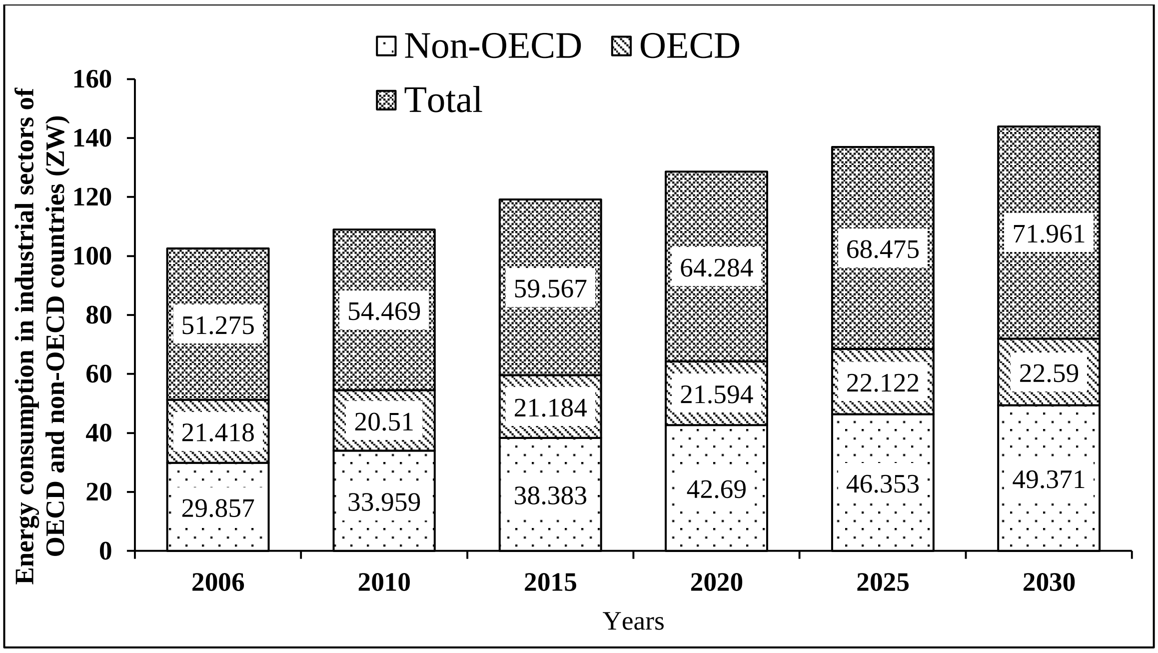

Figure 1.1. Energy consumption in industrial sectors of OECD and non-OECD countries by years

The distribution of energy consumption by fuel type between 2006 and 2030 in industrial sector can be seen in Figure 1.2.

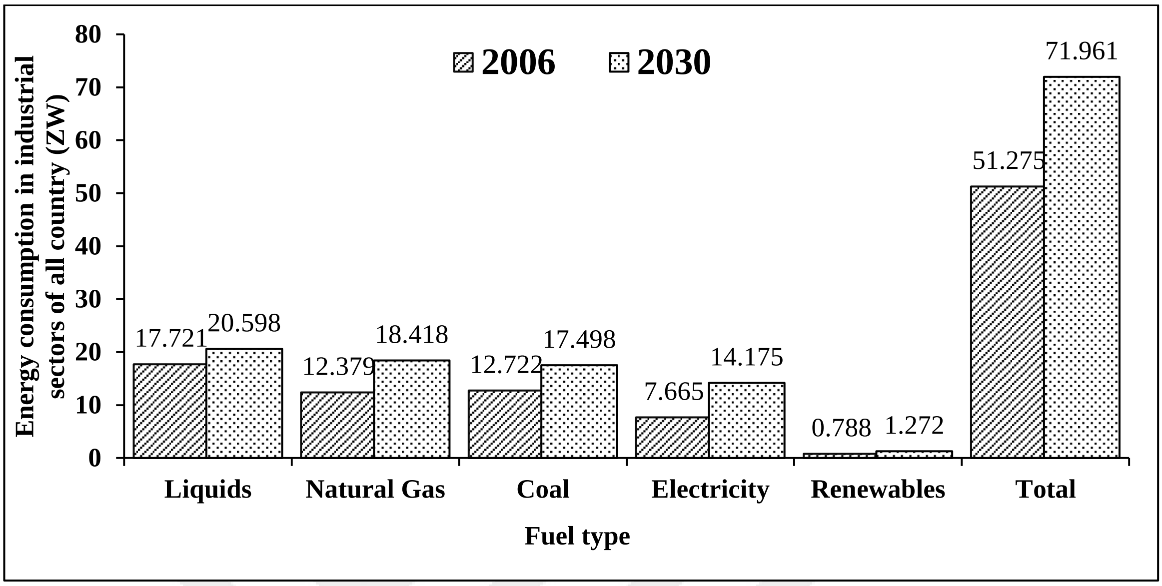

Figure 1.2. Energy consumption in industrial sectors of all countries by fuel types

Energy efficiency studies in the industry directly affect the cost of investments in a short time to pay itself can provide a serious advantage in competitive conditions. For this reason, energy efficiency studies in many countries are particularly concentrated in the industrial sector due to being effective and priority. Therefore, various methods have been developed that combine the thermodynamic results of a system with its economic and environmental effects.

Turkey's energy consumption is similar to the global consumption trend. According to the sectoral energy consumption statistics of 2017, 85.182% of Turkey's energy consumption is used in the industrial sector, while 14.818% is used in the service sector. 62% of the energy consumed in the industrial sector is consumed in the manufacturing industry. It is seen that natural gas consumption has a large share, especially in electricity generation. 62.2% of the electricity produced is still used in the manufacturing industry [4]. The distribution of energy consumption in Turkey by sectors is shown in detail in Figure 1.3. As seen in both figures, there is no significant decrease in dependence on fossil fuels. The export of natural gas used especially in thermal processes in such as ceramic sector will decrease the power of companies in our country to compete in global markets. Therefore, it is inevitable that businesses that do not use energy resources effectively and efficiently in production will fail under competitive conditions.

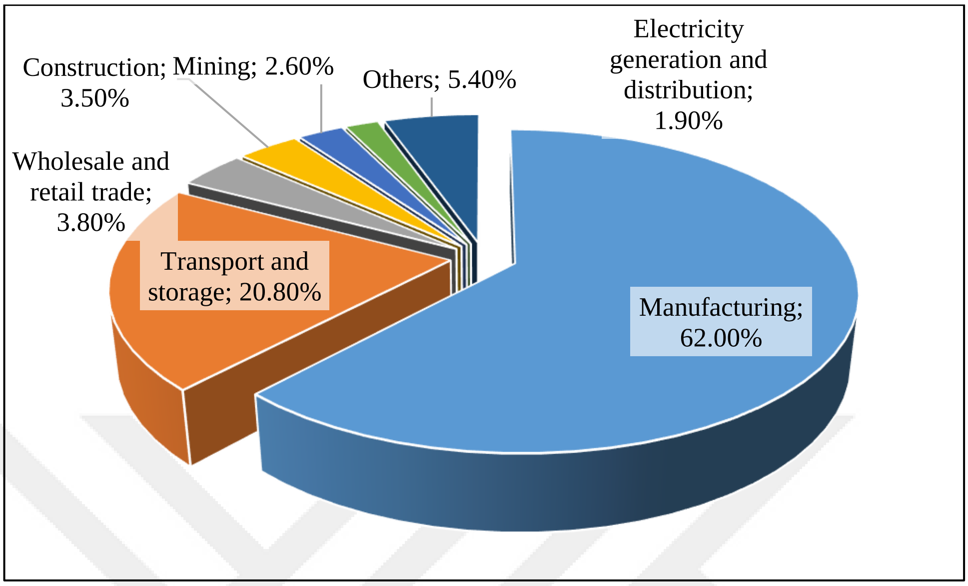

Figure 1.3. Distribution of energy consumption in Turkey by sectors in 2017

The fossil fuels such as oil and coal, which are the most important sources of energy, and their derivatives are rapidly depleting. Therefore, energy efficiency and energy saving issues are of great importance in Turkey, which is 73% dependent on external resources, as well as in global terms. In addition, in countries with energy-intensive manufacturing sectors such as Turkey, increasing energy efficiency leads to reduction of costs in a business, resulting in more competitive processes in the global market. In addition, due to the decrease in energy consumption, the dependence on imported energy decreases and energy price fluctuations can be prevented. Less energy use allows less emissions to be released into the environment, thereby improving air quality and reducing the global effects of climate change. Considering all these, when designing a system or a device with an engineering approach, it is necessary to consider the economical and environmental impact factors as well as the energy efficiency in the processes of that system or device. Therefore, various methods such as exergy, exergoeconomic and environmental analysis have been developed that combine the thermodynamic results of a system with its economic and environmental effects.

In the thermodynamic evaluation of a thermal system, it is more logical to perform exergy analysis than energy analysis. The results of exergy analysis generally indicate the contribution of improvements while making the processes in a system more comprehensible.

Because exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy, while a process becomes equilibrium with a reference environment. The exergy, which deals with the quality and usability of energy rather than the quantity of energy, is an important method in determining the causes, locations and magnitudes of inefficiencies of any system. In other words, exergy destruction and losses that occur in the systems and decrease the efficiency of the system are determined in exergy analysis [5].

Only thermodynamic performance evaluation is not sufficient when the improvements made according to the results of exergy analyses of a system are considered in terms of the cost of manufacturing the system. Therefore, exergoeconomic analysis is applied which determines the cost of exergy flow rates in the thermal system. To calculate the exergy flow cost of the thermal system, many expenses such as initial investment costs of the systems, raw materials, operating and maintenance cost, taxes, insurance costs of employees with depreciation, fuel, energy needs are evaluated over the lifetime of the system. According to the results obtained exergy destruction cost values allow us to compare the components of the system economically [6].

Exergoenvironmental analysis is performed to determine the environmental impact of a thermal system and improve its ecological performance. The environmental impact results, combined with exergy current rates, can be found exergy destruction environmental impact rate of system. Thus, by comparing the environmental effects of the components in the system, the component to be focused on can be found [7].

While conventional exergy analysis determines the magnitude and location of irreversibilities in a system, environmental and economic impacts resulting from exergy destruction are also determined. However, exergy analysis does not give us detailed information about exergy destruction. In addition, advance exergy analysis has been developed in order to find the causes of exergy destruction depending on the interaction between the components and to determine the real improvement potential of any component.

1.1. The purpose and importance of this study

Especially in the ceramic industry, which has thermal TL/m^{3}processes, with rising energy costs, the power to compete in global markets is decreasing every day. In ceramic factories in Turkey, between 35% and 40% of the production cost consists of energy costs. Around 75% of the energy cost is due to natural gas consumption. Furthermore, since there are continuous production lines in the ceramic industry, analyses are made on the total energy consumption, ignoring the irreversibilities that have occurred in the components so far. In addition, in case of power outages or fluctuations, re-starting up is difficult and expensive while the entire production line is stopped. Besides all these, depending on energy consumption, the intensive use of organic components (fuel and raw materials of ceramic) in the production process leads to a significant increase in the amount of carbon emissions. Therefore, the ever increasing electricity and natural gas prices for the ceramic industry become an important issue for employers in terms of cost and environment. The change in the price[1] of natural gas units in Turkey according to years is shown in Figure 1.

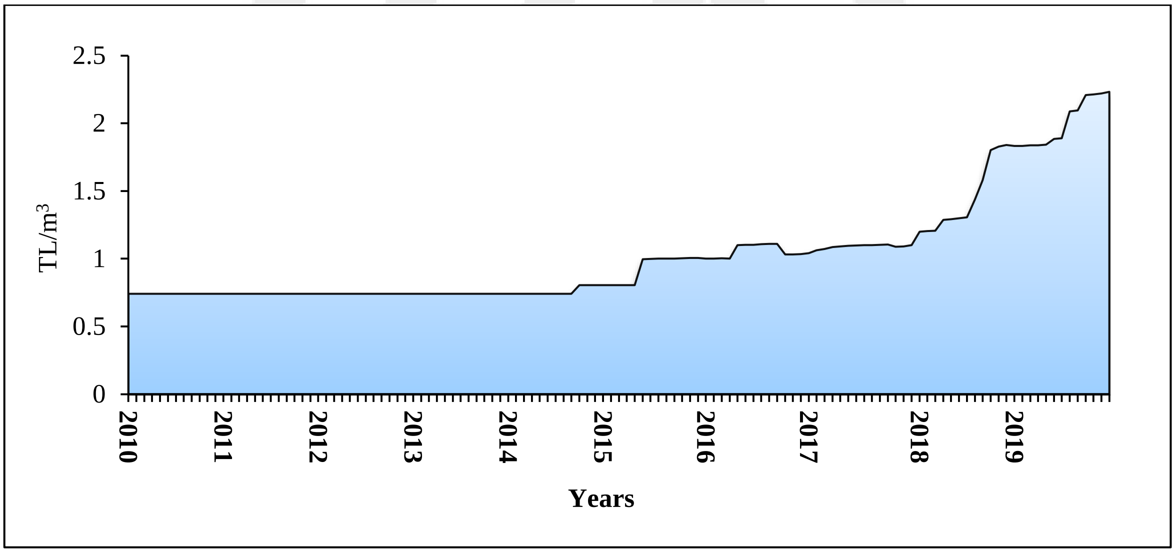

Figure 1.4. Change of natural gas unit price by years

In this study, a gas turbine cogeneration system in spray dryers is modeled for a ceramic factory to benefit environmentally and economically by reducing energy consumption. For this modeled cogeneration system, exergy analysis is performed first, so that the locations and magnitudes of the irreversibilities and their effects on the cost and environment can be

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[1] Prices for natural gas consumption between 10000 m^3 and 100000 m^3 per year

determined. Thus, a general improvement proposal can be given to the system. Also for this system, by performing advanced exergy analysis, the interactions of the components in the cogeneration system have effects on exergy destruction, and the actual improvement potentials of the components are determined. In addition, advanced exergoeconomic and advanced exergoenvironmental analyses are carried out to develop correct optimization strategies in all aspects of the system and to accurately determine the thermodynamic recovery potentials in the cogeneration system and its components. In this study, five different dead state temperatures are taken into account considering that ceramic production lines are affected by seasonal ambient temperatures. Thus, the exergetic effect of environmental temperature change is presented in this study. Although there are only a few exergy analysis studies related to the ceramic industry in the literature, there is no study that performs advanced exergy analysis for ceramic industry, this study may be a reference for the ceramic industry that wants to establish a cogeneration system.

2. LITERATURE VIEW

Morosuk and Tsatsaronis [8] demonstrated the method of calculating the endogenous/external and avoidable/unavoidable parts of exergy destruction by performing advanced exergy analysis for a simple gas turbine power system. As a result, it compared the results of advanced exergy analysis with conventional exergy analysis.

Contrary to the studies in the literature (product constant), Tsatsaronis and Morosuk [9] studied advanced exergy analysis of gas turbine and vapor-compression refrigeration machine under the assumption that the fuel of the whole system remained constant, and compared the results obtained, they noted the deviations in the values of the endogenous exergy destruction.

By performing exergy analysis and advanced exergy analysis of the combined cycle power factory, Petrakopoulou at al. [10] determined the interaction and development potential between the components. In this study, approximately 87% of the combustion chamber, which has the highest exergy destruction among the components, is composed of endogenous part, while 68% is unavoidable part. In addition, since the highest avoidable exergy destruction was also found in the combustion chamber, it was decided as the first component to focus on.

Soltani at al. [11] performed an externally-fired combined-cycle power plant integrated with biomass gasification advanced exergy analysis. Since the endogenous exergy destruction of all components in the system is higher than the exogenous exergy destruction, it has been found that their interaction with each other is weak. Authors emphasized that advance exergy analysis is more useful than exergy analysis, and that although combustion chamber and gasifier have the highest exergy destruction, the heat exchange is the first component to focus on because it has a higher avoidable exergy rate.

Emin at al. [12] investigated the performance of the electricity generation facility using advanced exergy analysis. In particular, it was emphasized that only the exergy analysis system may cause incomplete interpretation since it does not provide information about the interaction between the components. In the study, it was stated that the relationship between the components was weak since 70% of the total exergy destruction was caused by endogenous exergy destruction. In addition, the improvement potential of the whole system was found to be low (38%). It was understood that the focus should be on the combustion chamber and gas turbine with the highest avoidable exergy destruction.

Vuckovic at al. [13] conducted a study on real complex industrial plant using advanced exergy analysis and exergoeconomic performance evaluation. The steam boiler, which has the highest exergy destruction among the components, is determined to make up 80% of that total exergy destruction. In addition, more than 83.53% of steam boiler exergy destruction was found to be unavoidable exergy destruction. It has been estimated that efficiency can be increased by 7.44% by reducing the inevitable exergy destruction of the system by using lower exergoeconomic fuel costs and by making significant investment costs.

Wang at al. [14] performed conventional exergy analysis and advanced exergy analysis for the supercritical power plant. It was stated that the boiler sub system, which has the highest avoidable exergy destruction, should focus on not only the irreversibilities but also the irreversibilities in the other component. Especially 60% of feedwater preheaters' avoidable exergy destruction is exogenous part, it was determined that other components should focus on their improvement potential.

In order to examine the irreversibilities occurring in the turboprop engine used on the military training aircrafts in detail, Balli [15] conducted a conventional and advanced exergy analysis that examined exergy destruction by splitting endogenous/exogenous, avoidable/unavoidable and their combinations. Since 86% of the total exergy destruction of the system consists of endogenous exergy destruction, the relationship between the components was found weak. Since almost all of the exergy destruction consists of unavoidable exergy destruction (%94), the development potential of the system was found to be very low. Although the combustion chamber has the highest exergy destruction, its avoidable exergy destruction was found lower than the air compressor and power turbine. According to this result, only conventional exergy analysis showed that accurate interpretation may be insufficient.

Anvari at al. [16] researched advanced exergy and exergoeconomic analysis of the tri-generation system, which has a generating capacity of 40 MW heat generation, 2 MW cooling and 30 MW power. In this system, it was calculated that more than 32% of the total exergy destruction value and 33% of the total exergy destruction cost rate were caused by the avoidable part. As with other studies, the highest exergy destruction occurred again in the combustion chamber. For the whole system, the total exergy cost rate was found to be 29% endogenic part and 4% exogenous part. Although HRSG has the highest exergy destruction value compared to conventional exergy analysis, according to advanced exergy analysis, 71% of its exergy destruction was found to be made up of unavoidable parts. It was therefore determined that there should be a focus on pre-heather, which has a higher avoidable exergy destruction than HRSG.

Petrakopoulou at al. [17] performed an advanced exergoeconomic analysis of the mixed conducting membrane for oxy-fuel combustion system involving mixed processes. The author emphasized that although conventional exergy analysis provides information about the location and magnitude of inversions of complex and multi-component systems, it cannot determine the interactions between components, their dependence on each other, and their potential for development. For whole system, the exergy destruction cost rate is higher than the exogenous part, it has been found that the interaction between the components is not very strong. According to the conventional exergoeconomic analysis, it has been emphasized that it is not sufficient to identify the component with the highest investment cost rate and exergy destruction cost rate, such as the combustion chamber. In addition, such as the expander of the main gas turbine system, avoidable exergy destruction cost rate and avoidable investment cost rate should be focused on components.

Acıkkalp at al. [18] conducted an advanced exergoeconomic analysis of an electricity-generating facility that operates with natural gas with a total power generation capacity of 55 MW and an exergy efficiency of 40.2%. The exogenous exergy destruction cost rates of components such as air compressor, heat recovery steam generator and condenser have been determined to be higher than the endogenous part. According to this result, the interaction between these said components and other components is determined to be strong. Since the unavoidable exergy destruction cost rates of all components except the low-pressure steam generator and condenser was higher than the avoidable exergy destruction rate, it was stated that the development potential of the system is low. The endogenous part of the combustion chamber, which also has the highest rate of avoidable exergy destruction cost, is larger than the exogenous part. This has shown that the combustion efficiency in the combustion chamber can be improved.

Petrakopoulou at al. [19] applied advanced exergoenvironmental analysis for the combined-cycle power plant, combining the results from the life cycle assessment with exergy analysis. According to these results, the combustion chamber has the highest environmental impact, with the highest exergy destruction value, of which 68% was found to be unavoidable. It has also been found that the unavoidable environmental impact of most of the components in the whole plant is greater than that of the avoidable part. Accordingly, it has been determined that the system has low development potential in terms of environmental impact. In addition, components were found to be weak in their interaction between components because their endogenous environmental impact is higher than their exogenous part.

Acıkkalp at al. [20] studied conventional and advanced exergoenvironmental analyses of the electricity generation plant, which included consist of gas turbine and steam cycle. Firstly, exergy destruction results obtained from conventional exergy analysis were divided into endogenic/exogenous and unavoidable/avoidable parts and the results were combined with environmental impact and advanced exergoenvironmental results were obtained. In all components, the endogenous environmental impact was very large (80%) than the exogenous part, and accordingly the relationship between the components was found to be weak in terms of environmental impact. the system's potential for development has been determined to be very low, as the system's avoidable environmental impact rate is 33% of the total environmental impact rate. In addition, since the gas turbine and combustion chamber have a higher rate of avoidable endogenic environmental impact than other components, it has been determined that these components should be focused on.

3. THERMODYNAMIC AND ECONOMIC ANALYSIS

3.1. Energy Analysis

The first law of thermodynamics, which refers to the principle of conservation and transformation of energy, emphasizes that energy is a property related to thermodynamics. According to the principle of conservation of energy, energy cannot be existed when it exists, cannot be produced when it is not, but it can be converted to different forms with the help of physical and chemical processes. When a system changes its thermodynamic state, it can cross the system boundaries as energy, heat or work and the net change in the energy of the system is exactly equal to the net energy that crosses the system boundaries [21].

The first law of thermodynamics is expressed as follows;

For a closed system;

$$\delta Q = \Delta U + \delta W \tag{3.1}$$

For an open system

$$\delta Q = \Delta H + \delta W \tag{3.2}$$

where "δQ", "δW", "ΔU" and "ΔH" are heat, work, internal energy and enthalpy change per unit time in system, respectively.

Expressed thermodynamically, the net change in the total energy of a closed system during a state change is equal to the difference between the total energy entering the system and the total energy exiting the system.

$$\Delta E = E_2 - E_1 = (U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) \tag{3.3}$$

Where "E" is total energy, "KE" is kinetic energy, "PE" is potential energy, subscripts "1" and "2" are the first condition and the final state, respectively.

In closed systems, energy interactions occur with heat and work, while open systems with heat, work and mass. Firstly, the mass balance of a system is determined as [22];

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \tag{3.4}$$

where $\dot{m}$ is mass flow rate of open system and subscripts "in" and "out" means inlet and outlet conditions.

According to the principle of conservation of energy for a continuous flow system, the first law equation of thermodynamics can be written as follows [22-23];

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out} \left(h_{out} + \frac{V_{out}^2}{2} + g z_{out} \right) - \sum \dot{m}_{in} \left(h_{in} + \frac{V_{in}^2}{2} + g z_{in} \right) \tag{3.5}$$

where “ V”, “g” and “z” are velocity of materials, acceleration of gravity and potential height of materials, “$\dot{m}$” is the mass flow rate and subscripts “in” and “out” means inlet and outlet, respectively.

3.2. Conventional Exergy Analysis

When it is desired to obtain power from an energy source, the availability of that energy is important rather than the amount of energy. The main objective is to determine the part of the amount of energy that can be converted into useful work. Exergy is defined as the maximum useful work that can be achieved when a thermodynamic system is balanced with the surrounding environment by passing reversible state changes. In other words, the exergy, which takes into account the quality as well as the quantity of an energy source, can also be defined as the maximum work it can do in the environment it is employed.

Exergy analysis provides information about the quality of the losses occurring in a system, as well as the location and amount of the losses, and the methods to be applied to reduce the losses.

If the exergy flows transferred by work, heat, mass and current are written separately, the general exergy balance equation for a control volume is written as follows [24];

$$\sum \left(1 - \frac{T_0}{T_i} \right) \dot{Q} - \dot{W} + \sum \dot{m}_{in} \psi_{in} - \sum \dot{m}_{out} \psi_{out} - \dot{E}x_D = 0 \tag{3.6}$$

where “T_i” is the operating temperature, “T_0” is dead state condition temperature, “$\dot{Q}$” is the heat transfer rate through the boundary, “$\dot{W}$” is the mechanical work rate, , “ψ” is the stream exergy rate and “$\dot{E}x_D$” is the exergy destruction rates of the system.

If exergy flows transferred by work, heat, mass and current are considered as a whole and it is assumed that there is no work and heat exergy transfer, the exergy balance equation from can be shown as follows;

$$\dot{E}x_D = \sum_{in} \dot{E}x_{in} - \sum_{out} \dot{E}x_{out} \tag{3.7}$$

In the above equation, at any *k*th control volume, if the system is defined as fuel "$\dot{E}x_{F,k}$" to the entering materials and products to the materials leaving "$\dot{E}x_{P,k}$" the system, the exergy balance equation can be written as follows.

$$\dot{E}x_D = \dot{E}x_{F,k} - \dot{E}x_{P,k} \tag{3.8}$$

Assuming that there are no nuclear, magnetic, electrical, surface stress and friction effects in the thermal system, the exergy of any substance can be determined as follows;

$$\dot{E}x_{total} = \dot{E}x^{ph} + \dot{E}x^{ch} + \dot{E}x^{p} + \dot{E}x^{k} \tag{3.9}$$

where "$\dot{E}x^{ph}$", "$\dot{E}x^{ch}$", "$\dot{E}x^{p}$", "$\dot{E}x^{k}$" are physical exergy, chemical exergy, potential exergy and kinetic exergy, respectively. In this study, the kinetic and potential exergy will be neglected as in many other studies.

The physical (thermomechanical) exergy is the maximum work achieved during the equilibrium of temperature "T_i" and pressure "P_i" of any substance through reversible processes with ambient temperature "T_0" and ambient pressure " P_0".

The physical (thermomechanical) exergy can be detected as follows;

- For a closed system;

$$\dot{E}x^{ph} = \dot{m}_i[(u_i - u_0) + P_0(v_i - v_0) - T_0(s_i - s_0)] \tag{3.10}$$

$$u_i - u_0 = c_v(T_i - T_0) \tag{3.11}$$

where "u" is internal energy, "m" is mass flow rates "s" is entropy, "T" is temperature, "P" is pressure and "v" is specific volume, "c" is specific heat capacity (kJ/kgK). Also "i" means ith component, and "0" means dead state condition.

The specific heat capacity "c_p" of natural gas, exhaust gas or flue gas at constant pressure can be calculated as [25];

$$\overline{c}_p = a + bT + cT^2 + dT^3 \tag{3.12}$$

The coefficients "a, b, c, d" of some gases, which are a function of the temperature used in the specific heat calculation (equation 1), are given in Table 3.1 [25] .

Table 3.1. Coefficients "a,b,c,d" of some gases

Contents	**Chemical formula**	**a**	**b ($\times 10^{-2}$)**	**c ($\times 10^{-5}$)**	**d ($\times 10^{-9}$)**
N_2	Nitrogen	28.90	-0.1571	0.8081	-2.873
O_2	Oxygen	25.48	1.520	-0.7155	1.312
H_2	Hydrogen	29.11	-0.1916	0.4003	-0.8704
CO	Carbon monooxide	28.16	0.1675	0.5372	-2.222
CO_2	Carbon dioxide	22.26	5.981	-3.501	7.469
H_2O (g)	Water (gas)	32.24	0.1923	1.055	-3.595
CH_4	Methane	19.89	5.024	1.269	-11.01
C_2H_6	Ethane	6.9	17.27	-6.406	7.285
C_3H_8	Propane	-4.04	30.48	-15.72	31.74
C_4H_{10}	n-Butane	3.96	37.15	-18.34	35.00
C_4H_{10}	i-Butane	-7.913	41.60	-26.01	49.91
C_5H_{12}	n-Pektane	6.774	45.43	22.46	42.29
C_5H_{12}	n-Hexane	6.938	55.22	-28.65	57.69
C_2H_4	Ethene	3.95	15.64	-8.344	17.67
C_3H_6	Propylene	3.15	23.83	-12.18	24.62

- For a steady state and open system, the exergy rate of materials can be expressed by the following equations [22-23];

$$\dot{E}x^{ph} = \dot{m}_i[(h_i - h_0) - T_0(s_i - s_0)] \tag{3.13}$$

$$h_i - h_0 = c_p(T_i - T_0) \tag{3.14}$$

$$s_i - s_0 = c_p ln\left(\frac{T_i}{T_0}\right) - Rln\left(\frac{P_i}{P_0}\right) \tag{3.15}$$

where "R" is universal gas constant.

Using the above equations;

- The general physical exergy rate of the gases can be written as follow [22-24];

$$\dot{E}x^{ph}_{gas} = \dot{m}_i\left[c_{p,i}\left((T_i - T_0) - T_0 ln\left(\frac{T_i}{T_0}\right)\right) + RT_0 ln\left(\frac{P_i}{P_0}\right)\right] \tag{3.16}$$

- The general physical exergy rate of the solid materials and liquids can be calculated as [24];

$$\dot{E}x^{ph}_{solid,liquid} = \left[c_{v,i}\left((T_i - T_0) - T_0 ln\left(\frac{T_i}{T_0}\right)\right) - v_m(P_i - P_0)\right] \quad (3.17)$$

where v_m indicates the specific volume obtained at T_0.

The coefficients "a, b, c, d" of some gases, which are a function of the temperature used in the specific heat calculation (eq. 3.12), are given in Table 3.1.

The chemical exergy is the maximum amount of work achieved during chemical reactions to equilibrium with the environment.

For gas mixtures, the specific chemical exergy rates "$\overline{e}^{ch}_{ex}$" can be calculated as [22-23,26];

$$\overline{e}^{ch}_{ex} = \sum x'_k \overline{e}^0_k + \overline{R}T_0 \sum x'_k ln x'_k \quad (3.18)$$

where "$\overline{e}^0_k$" is specific molar chemical exergy rate of any molecule (kJ/kmol), "x'" is mole rate and "$\overline{R}$" is universal gas constant (kJ/kmol).

It is assumed that substances such as "C_xH_y" can react fully with "O_2" "CO_2", and "H_2O", to calculate standard chemical exergy "C_xH_y". Accordingly, the molar Gibbs function for "C_xH_y" is indicated below [22-23,26];

$$\overline{e}^{ch}_F = \left[\overline{g}_{C_xH_y} + \left(a + \frac{b}{4}\right)\overline{g}_{O_2} - a\overline{g}_{CO_2} - \frac{b}{2}\overline{g}_{H_2O(l)}\right](T_0, p_0)$$
$$+ a\overline{e}^{ch}_{CO_2} + \left(\frac{b}{2}\right)\overline{e}^{ch}_{H_2O(l)} - \left(a + \frac{b}{4}\right)\overline{e}^{ch}_{O_2} \quad (3.19)$$

where "$\overline{g}_i$" is molar gibbs function of *i*th substance.

The specific chemical exergy ratio of hydrocarbons commonly used in the literature and obtained experimentally is calculated as follows by correlating with "LHV" [27-28].

$$\overline{e}^{ch}_{ex,C_xH_y} = \gamma_{f,C_xH_y} LHV_{C_xH_y} \quad (3.20)$$

where "LHV" is lower heating value of substances and "γ_f" is exergy coefficient of the specific exergy ratio. The specific exergy ratios of some hydrocarbons are listed in Table 3.2 [29].

Table 3.2. Specific exergy ratios of some hydrocarbons calculations

Substances	The specific chemical exergy formulas
Solids	For $\frac{O}{C} \leq 0.5$; $\frac{\bar{e}_{ex}^{ch}}{LHV} = \gamma_f \cong 1.0438 + 0.0158\frac{H}{C} - 0.0813\frac{O}{C} + 0.0471\frac{N}{C}$ (3.21)
	For $\frac{O}{C} > 0.5$; $\frac{\bar{e}_{ex}^{ch}}{LHV} = \gamma_f \cong \frac{1.0438+0.0158\frac{H}{C}-0.3343\frac{O}{C}\left(1+0.0609\frac{H}{C}\right)+0.0447\frac{N}{C}}{1-0.4043\frac{O}{C}}$ (3.22)
Fluids	$\frac{\bar{e}_{ex}^{ch}}{LHV} = \gamma_f \cong 1.0374 + 0.0159\frac{H}{C} + 0.0567\frac{O}{C} + 0.05985\frac{S}{C}\left(1 - 0.1737\frac{H}{C}\right)$ (3.23)
	$\frac{\bar{e}_{ex}^{ch}}{LHV} = \gamma_f \cong 1.04224 + 0.011925\frac{H}{C} - 0.042\frac{1}{C}$ (3.24)
	$\frac{\bar{e}_{ex}^{ch}}{LHV} = \gamma_f \cong 1.0401 + 0.01728\frac{H}{C} + 0.0432\frac{O}{C} + 0.2196\frac{S}{C}\left(1 - 2.0628\frac{H}{C}\right)$ (3.25)
Gases	$\frac{\bar{e}_{ex}^{ch}}{LHV} = \gamma_f \cong 1.0334 + 0.0183\frac{H}{C} - 0.0694\frac{1}{C}$ (3.26)
	$\frac{\bar{e}_{ex}^{ch}}{LHV} = \gamma_f \cong 1.033 + 0.0169\frac{H}{C} - 0.0698\frac{1}{C}$ (3.27)

The exergy transfer occurring during heat transfer is determined as follows [22];

$$\dot{E}x_Q = \left(1 - \frac{T_0}{T_i}\right)\dot{Q} \tag{3.28}$$

The exergy transfer with work is shown below;

$$\dot{E}x_W = \dot{W} - p_0(V_i - V_0) \tag{3.29}$$

3.2.1. System performance parameters obtained from exergetic values

The data obtained from exergy analysis are evaluated by various methods. Thus, more detailed information about the system and its components is obtained. It can be understood which component has the most effect on exergy losses and destruction in the system. These methods are described below, respectively [30].

- ***Exergy efficiency "ψ":*** There are two different exergy efficiency approaches in the literature;

  Firstly, universal exergy efficiency is expressed below;

  $$\psi_{universal} = \frac{\dot{E}x_{in}}{\dot{E}x_{out}} \tag{3.30}$$

  The other is the following product and fuel-based functional exergy efficiency to be used in this study;

  $$\psi_{func} = \frac{\dot{E}x_{P,k}}{\dot{E}x_{F,k}} \tag{3.31}$$

- ***Sustainability assessment* "*SI*":** While using the limited energy source on earth for the comfort of the ongoing humanity, processes should also be designed to provide maximum benefit. In order for a system to use its energy source in the most effective way and to ensure its continuity, it must be high in exergy efficiency. Therefore, Sustainability Index "SI" is known to be related to exergy efficiency. Thus, it is ensured that existing resources can be used in future societies through processes with maximum exergy efficiency. The Sustainability Index demonstrates the potential to improve the system [31-32].

  $$SI = \frac{1}{1-\psi} \tag{3.32}$$

- ***Relative exergy consumption rate "ϕ":*** Relative exergy consumption rate is a measure of the ratio of exergy losses occurring in the *k*th component to exergy losses occurring throughout the system [20].

$$\phi = \frac{\dot{E}x_{D,k}+\dot{E}x_{loss,k}}{\dot{E}x_{D,total}+\dot{E}x_{loss,total}} \tag{3.33}$$

- ***Product exergy consumption rate "ϑ":*** It is defined as the ratio of the exergy consumption value that occurs in any *k*th component of the system to the total product exergy produced by the system [20,33].

$$\vartheta = \frac{\dot{E}x_{D,k}+\dot{E}x_{loss,k}}{\dot{E}x_{P,total}} \tag{3.34}$$

- ***Fuel exergy consumption rate "φ":*** It is expressed as the ratio of the exergy consumption value occurring in any *k*th component of the system to the total fuel exergy provided to the system [20,33].

$$\varphi = \frac{\dot{E}x_{D,k}+\dot{E}x_{loss,k}}{\dot{E}x_{F,total}} \tag{3.35}$$

- ***Exergy improvement potential "$\dot{E}xI\dot{P}_k$":*** In order to achieve maximum improvement in energy efficiency, it can be realized by minimizing exergy consumption rate. The potential for exergy development shows us the exergy rate that can be recovered from the exergy consumption rate. Thus, it can be seen in which component improvement has more effect on exergy efficiency [33].

$$\dot{E}xI\dot{P}_k = (1-\psi_k)\left(\dot{E}x_{D,k}+\dot{E}x_{loss,k}\right) \tag{3.36}$$

3.3. Exergoeconomic Analysis

It is seen as the main purpose to operate a system under optimum conditions by evaluating only thermodynamically. However, the actual costs of products and fuels should be determined by evaluating the system economically. Therefore, it is necessary to know the economic equivalent of thermodynamic properties when designing a system. The main objective is to obtain products with maximum efficiency and minimum cost.

Exergoeconomic analysis is a useful method for engineers and researchers, using exergy analysis and economic analysis together to determine the actual cost of the product. The exergoeconomic analysis method provides an understanding of the cost of exergy destruction in thermal systems and the effects of components on the system in terms of cost. In order to determine the costs of the products, the initial investment costs, operating and maintenance costs, taxes, insurance, depreciation, employee costs, fuel and raw material costs are determined over the life of the system. Costs of material and energy flows in the system are calculated with the cost balance and additional cost equations written separately for each component. In the literature, there are many approaches to exergoeconomic analysis [5,29];

- Exergy Economics Approach (EEA)
- First Exergoeconomic Approach (FEA)
- Exergetic Cost Theory (ECT)
- Thermoeconomic Functional Analysis (TFA)
- Engineering Functional Analysis (EFA)
- Last-In–First-Out Approach (LIFOA)
- Structural Analysis Approach (SAA)

In addition to these methods, the most preferred and frequently used method is SPECO (Specific Exergy Costing) method in the literature. In some studies, EXCEM (Exergy, Cost, Energy and Mass) method was also used. In this study, these methods are explained in the other section because they are applied in both methods.

3.3.1. SPECO (Specific Exergy Costing) method

SPECO method, which combines exergy flows and costs, is carried out by following the steps below [34];

- Firstly, the exergy analysis, which forms the basis of this study, is carried out and the exergy flow entering and exiting the system and exergy destruction are determined.
- The exergy current, expressed as fuel and product, is calculated separately for each component.
- The cost per unit of exergy "c_k" is obtained for each exergy flow. Then, the cost of the exergy stream "$\dot{C}_k$" is determined by multiplying the unit cost stream value of the component under consideration with the exergy flow value "Ex_k". The material-energy flows entering "$\dot{E}x_{in}$" and exiting "$\dot{E}x_{out}$" the system and the heat "$\dot{E}x_q$" and work "$\dot{W}$" related exergy values are converted into cost flows as follows;

$$\dot{C}_{in} = c_{in}\dot{E}x_{in} \tag{3.37}$$

$$\dot{C}_{out} = c_{out}\dot{E}x_{out} \tag{3.38}$$

$$\dot{C}_W = c_W\dot{W} \tag{3.39}$$

$$\dot{C}_q = c_q\dot{E}x_q \tag{3.40}$$

Cost balance applied to any system component; shows that all exergy flows exiting are equal to the sum of the exergy flows entering and the initial investment, operation and maintenance costs. The cost balances for each component can be formulated as below:

$$\sum \dot{C}_{in,k} + \dot{C}_{q,k} + \dot{Z}_k = \sum \dot{C}_{out,k} + \dot{C}_{w,k} \tag{3.41}$$

This equation can be written in terms of unit exergy costs as follows;

$$\sum\left(c_{in}\dot{E}x_{in}\right)_k + c_{q,k}\dot{E}x_{q,k} + \dot{Z}_k = \sum\left(c_{out}\dot{E}x_{out}\right)_k + c_{w,k}\dot{W}_k \tag{3.42}$$

where $\dot{Z}_k$ is total investment and operation-maintenance costs.

In general, if one component is considered to have the number *N* exergy current input, the balance equation with the number *N* unknown occurs. Therefore, we need the number *N-1* auxiliary equations. That is, additional equations are needed to perform the exergoeconomic calculation. Rule *P* (on the product exergy current side) and *F* rule (on the fuel exergy current side) are used to determine the auxiliary equations so that a sufficient number of equations can be written for the solution.

- **The *F* principle (Fuel exergy stream side);** Exergy flow entering any component is defined as the fuel of that component and expresses the cost of that exergy flow equal to the average exergy costs of the previous exergy flow [29].
- **The *P* principle (Product exergy stream side):** It considers the product current of any system component equal to the cost of the fuel flow entering the system [29].

When the balances for all components are solved, the unit cost flow value for each component is also obtained. The average unit costs of fuel, product, destruction, loss exergy of a component within the system are calculated as follows:

$$\dot{C}_F = c_F \dot{E}x_F \tag{3.43}$$

$$\dot{C}_P = c_P \dot{E}x_P \tag{3.44}$$

$$\dot{C}_D = c_F \dot{E}x_{dest} \tag{3.45}$$

$$\dot{C}_L = c_F \dot{E}x_{loss} \tag{3.46}$$

The exergoeconomic analysis uses two important parameters to evaluate the components in the system;

- **The exergoeconomic factor “f_k”:** The exergoeconomic factor is determined by the ratio of the investment cost to the sum of the exergy consumption and investment cost, which constitutes the total cost. This factor reveals the effect of exergy consumption cost on total cost. This analysis shows the importance of exergy consumption cost as well as investment cost [35].

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + (\dot{C}_{D,k} + \dot{C}_{L,k})} \tag{3.47}$$

- **The relative cost difference "r_k":** The relative cost difference in exergoeconomic analysis is the average cost increase per unit exergy between fuel and product of a given component [35].

$$r_k = \left(\frac{c_{P,k} - c_{F,k}}{c_{F,k}}\right) = \frac{c_{F,k}\left(\dot{E}x_{D,k} + \dot{E}x_{loss,k}\right) + \dot{Z}_k}{c_{F,k}\dot{E}_{P,k}} \tag{3.48}$$

The capital cost "$\dot{Z}_k$" flow used in both parameters is determined as follows [36];

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \tag{3.49}$$

where "$\dot{Z}_k^{CI}$" is the investment cost and "$\dot{Z}_k^{OM}$" is the cost of operation and maintenance. The following processes are followed to calculate the investment cost;

- The present monetary value "$\dot{P}\dot{W}$" is calculated as;

$$\dot{P}\dot{W}_{system} = T\dot{C}I_{system} - \dot{S}_{system}PWF_{(i,n)} \tag{3.50}$$

where "$T\dot{C}I_{system}$" is the total capital of investment, "$\dot{S}_{system}$" is the salvage value, "PWF" is the present worth factor, "i" is the interest rate and "n" is the number of periods in which interest is applied.

- The present worth factor "PWF" is determined as;

$$PWF = 1/(1+i)^n \tag{3.51}$$

- The salvage value "$\dot{S}_{system}$" can be expressed as;

$$\dot{S}_{system} = T\dot{C}I_{system}\mu \tag{3.52}$$

where "μ" is the salvage value percentage.

- The annual capital cost is calculated as "$\dot{C}\dot{A}_{system}$";

$$\dot{C}\dot{A}_{system} = \dot{P}\dot{W}_{system}CRF \tag{3.53}$$

- The recovery factor of initial capital cost "CRF" can be written as;

$$CRF = [i(1+i)^n]/[(1+i)^n - 1] \tag{3.54}$$

- The hourly levelized capital investment cost of system can be determined as;

$$\dot{Z}_{system} = \frac{\Omega\dot{C}\dot{A}_{system}}{3600\ (s\ h^{-1})\tau\ (h\ year^{-1})} \tag{3.55}$$

where "τ" is the the annual working hour and "Ω" is the operation and maintenance factor. In some studies in the literature, since the cost of operation and maintenance is not calculated, “Ω” is assumed to be 1.06. In the studies where cost of operation and maintenance can be determined, “Ω” is accepted as 1 and the hourly levelized capital investment cost “$\dot{Z}^{CI}_{system}$” is rearranged as follows;

$$\dot{Z}^{CI}_{total} = \frac{\dot{C}\dot{A}_{system}}{3600\ (s\ h^{-1})\tau\ (h\ year^{-1})} \tag{3.56}$$

- The hourly levelized capital investment cost of *k*th component can be determined as;

$$\dot{Z}^{CI}_{k} = \dot{Z}^{CI}_{system}\frac{PEC_k}{\sum_{system} PEC_k} \tag{3.57}$$

- The hourly operation and maintenance cost of *k*th component can be expressed as follows;

$$\dot{Z}^{OM}_{k} = \dot{Z}^{OM}_{system}\frac{PEC_k}{\sum_{system} PEC_k} \tag{3.58}$$

where “PEC” is the cost of the purchased equipment.

“PEC” values for the components of the gas turbine unit (Air compressor(AC), combustion chamber(CC), gas turbine(GT)) investigated in this study can be calculated as follows [37];

$$PEC_{AC} = \frac{(71.1)\dot{m}_{AC,air}\left(\frac{P_{AC,out}}{P_{AC,in}}\right)ln\left(\frac{P_{AC,out}}{P_{AC,in}}\right)}{(0.92)-\eta_{AC}} \tag{3.59}$$

$$PEC_{CC} = \frac{(46.08)\dot{m}_{CC,air}\left[1+exp\left((0.018)T_{CC,in}-26.4\right)\right]}{\left[(0.995)-\left(\frac{P_{GT,in}}{P_{CC,in}}\right)\right]} \tag{3.60}$$

$$PEC_{GT} = \frac{(479.34)\dot{m}_{GT,air}ln\left(\frac{P_{GT,in}}{P_{GT,out}}\right)\left[1+exp\left((0.036)T_{GT,in}-54.4\right)\right]}{(0.9)-\eta_{GT}} \tag{3.61}$$

3.3.2. EXCEM (Exergy–cost–energy–mass) analysis

According to the first law of thermodynamics, energy and mass can neither be consumed nor destroyed, but can only change form. According to this law, which is also known as the law of conservation of mass and energy, general mass and energy equations are written as follows [8,38];

$$\dot{m}_{in} - \dot{m}_{out} = \dot{m}_{acc} \tag{3.62}$$

$$\dot{E}_{in} - \dot{E}_{out} = \dot{E}_{acc} \quad (3.63)$$

where “acc” means accumulated.

The waste energy output rate “$\dot{L}_{en}$” occurring in the system is indicated as follows;

$$\dot{L}_{en} = \sum \dot{E}_{in} - \sum \dot{E}_{out} \quad (3.64)$$

The irreversibility of the processes causes increased entropy and exergy consumption. The general exergy equation is shown below [8,38];

$$\dot{E}x_{in} - \dot{E}x_{out} + \dot{L}_{ex} = \dot{E}_{acc} \quad (3.65)$$

“$\dot{L}_{ex}$” is the sum of the waste exergy from the system and the exergy loss that occurs in the system due to irreversibility;

$$\dot{L}_{ex} = \dot{E}x_{loss} + \dot{E}x_{dest} \quad (3.66)$$

In contrast to exergy consumption, the cost is increased and unprotected. The cost generation rate refers to the appropriate capital and other costs required to establish and maintain a system. The general balance equation of cost can be written as;

$$K_{in} + K_{gen} - K_{out} = K_{acc} \quad (3.67)$$

where “K_{gen}” is related to the appropriate capital and other costs.

In the EXCEM method, it is seen that only capital costs are used, since the use of the term cost generation leads to the complexity of the analysis, and many cost unknowns (interest rates, salvage value, number of working hours per year, component lifetimes) cause complexity in the analysis. In total cost generation, only capital costs can be taken into account when the ratio of capital costs is too high. Since there is the same directional relationship between capital costs and other cost generation components, the tendency between total cost generation and capital costs is also in the same direction.

In order to evaluate a system from a thermoeconomic point of view, the parameters “$\dot{R}$” used in EXCEM method are used. This parameter is determined by the ratio of consumption and waste energy obtained as a result of energy and exergy analysis to capital cost [8,38].

- If the energy losses are considered, the exergoeconomic cost parameter is calculated as follows;

$$\dot{R} = \frac{\dot{L}_{en}}{K} \tag{3.68}$$

- If the exergy losses and destruction are considered, the exergoeconomic cost parameter is calculated as follows [39];

$$\dot{R}_{ex} = \frac{\dot{L}_{ex}}{K} \tag{3.69}$$

In this study, since SPECO method and EXCEM analysis are applied to the same system, cost values are considered the same ($/h)

$$\dot{Z}_{system} = K_{system} \tag{3.70}$$

3.4. Exergoenvironmental Analysis

Exergoenvironmental is associated with the lifetime of energy systems by assessing the location, size and resources of the environmental impact. This analysis uses the LCA method, a technique to evaluate the environmental impact rate associated with a product throughout its life cycle. For the LCA method, ECO-indicator99 is used to identify the environmental impacts associated with system components and exergy carriers. The ECO-indicator99 provides data for calculating and evaluating the impact of materials used in each process component. According to ECO-indicator99, environmental impacts are evaluated in three categories of damage: (1) damage to human health, (2) damage to the ecosystem and (3) depletion of resources. This indicator, which describes the overall environmental impact rate associated with system components and exergy carriers, is indicated by "ecopoints (Pts=1000 mPts)", a dimensionless unit. There is a linear relationship between the magnitude of this indicator "Pts" and the negative impact of a system on the environment [40].

The exergoenvironmental analysis consists of three steps;

- The exergy analysis is performed for a thermodynamic system and all its components.
- The inductor "Pts" values are found by performing life cycle assessment (LCA) for all components of the system and all input currents entering the system.
- The exergoenvironmental values are calculated by combining environmental impact rate indicators obtained from LCA with exergy current values. With the help of

exergoenvironmental values, component with the highest environmental impact rate can be found.

The general algorithm of the exergoenvironmental method is shown in Figure 3.1 [40].

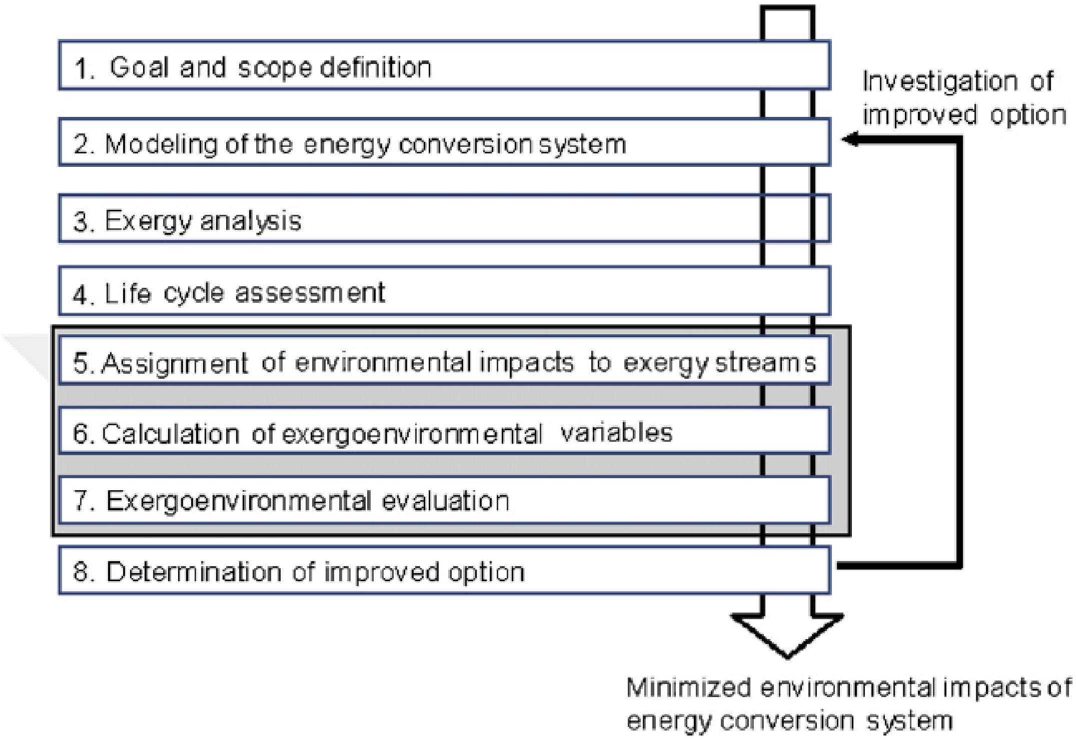


Figure 3.1. General algorithm of the exergoenvironmental method

The exergy values are assigned to environmental impact rate in exergoenvironmental analysis, as well as costs in exergoeconomic analysis. The environmental impact rate "$\dot{B}_j$" (Pts/h) of any mass flow "j" is equal to the multiplication of the exergy rate $\dot{E}x_j$" by the specific environmental impact rate "b_j" (Pts/GJ) [41].

$$\dot{B}_j = b_j \dot{E}x_j \tag{3.71}$$

The environmental impact rate streams associated with work and heat transfers are calculated as follows, respectively [41];

$$\dot{B}_q = b_q \dot{E}x_q \tag{3.72}$$

$$\dot{B}_w = b_w \dot{W} \tag{3.73}$$

In addition to the environmental impact rate of the mass flow into the component, the environmental impact rate associated with the lifecycle of the component itself "$\dot{Y}_k$" (Pts/h) occurs [19, 37].

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \tag{3.74}$$

where "$\dot{Y}_k^{CO}$", "$\dot{Y}_k^{OM}$" and "$\dot{Y}_k^{DI}$" are the lifecycle phases of construction "CO" (including manufacturing, transport and installation), operation and maintenance "OM" and disposal "DI", respectively.

In the *k*th component, the total environmental effects associated with the pollutant formation "$\dot{B}_k^{PF}$"of the gases such as CH_4, CO_2, CO, NO_2, NO_x and SO_x emitted as a result of chemical reactions are calculated as follows [19, 42]:

$$\dot{B}_k^{PF} = \sum_i b_i^{PF}\left(\dot{m}_{i,out} - \dot{m}_{i,in}\right) \tag{3.75}$$

where $\dot{m}_{i,out}$ and $\dot{m}_{i,out}$ are the mass flow rates of the *i*th substance leaving and entering the *k*th component.

The environmental impact rate balance for the *k*th component can be written as [42-43];

$$\sum_{j=1}^{n} \dot{B}_{j,k,in} + \left(\dot{Y}_k + \dot{B}_k^{PF}\right) = \sum_{j=1}^{n} \dot{B}_{j,k,out} \tag{3.76}$$

$$\sum_{j=1}^{n}\left(b_j \dot{E}x_j\right)_{k,in} + \left(\dot{Y}_k + \dot{B}_k^{PF}\right) = \sum_{j=1}^{n}\left(b_j \dot{E}x_j\right)_{k,out} \tag{3.77}$$

The following variables are used to evaluate environmental performance of system components;

- The specific environmental impacts of product and fuel for the *k*th component can be written respectively as;

$$b_{P,k} = \frac{\dot{B}_{P,k}}{\dot{E}x_{P,k}} \tag{3.78}$$

$$b_{F,k} = \frac{\dot{B}_{F,k}}{\dot{E}x_{F,k}} \tag{3.79}$$

- The exergy destruction and loss environmental impact rate of *k*th component is calculated as follows;

$$\dot{B}_{D,k} = b_{f,k} \dot{E}x_{D,k} \tag{3.80}$$

$$\dot{B}_{L,k} = b_{f,k}\dot{E}x_{loss,k} \tag{3.81}$$

- In terms of environmental impact, the exergoenvironmental factor “$f_{b,k}$” used to compare the components in the system is determined by the ratio of the environmental impact rate of the *k*th component “$\dot{Y}_k$” to the total environmental impact rate “$\dot{Y}_k + \dot{B}_{D,k} + \dot{B}_{L,k}$” [42-43].

$$f_{b,k} = \frac{\dot{Y}_k+\dot{B}_k^{PF}}{\dot{Y}_k+\left(\dot{B}_{D,k}+\dot{B}_{L,k}+\dot{B}_k^{PF}\right)} \tag{3.82}$$

- The relative difference of specific environmental impact rate “$r_{b,k}$” is used for the potential to reduce or improvement the environmental impact rate of the *k*th component [42-44].

$$r_{b,k} = \frac{b_{P,k}-b_{F,k}}{b_{F,k}} \tag{3.83}$$

3.5. Advanced Exergy Analysis

With the help of conventional exergy analysis, the causes, locations and magnitudes of the irreversibilities occurring in a system can be determined, while the effects of exergy results on the cost and the environment can be found. It provides real information in suggesting general improvement recommendations for the system and its components. However, convectional exergy analysis is not sufficient to calculate the irreversibilities resulting from the interaction between components or to calculate the actual improvement potential of the components. In particular, given a system of components that work in conjunction with each other, it may lead to incorrect analysis if interactions between components are not included in the calculations. Especially when considering complex systems of components that work in conjunction with each other, ignoring their interaction with each other causes inefficient system design as well as misinterpretations. The advanced exergy analysis prevents these results from occurring since it evaluates the relationship between all its components. The exergy destruction occurring in the components can be divided into the following sections [45];

- The endogenous exergy destruction “$\dot{E}x_{D,k}^{EX}$” is the part of exergy destruction in the component under study resulting from the interaction of other components in the system.

- The exergy destruction of the components in the system from their own working conditions is called endogenous exergy destruction "$\dot{E}x_{D,k}^{EN}$".
- Some of the exergy destruction of the components in the system are called with avoidable exergy destruction "$\dot{E}x_{D,k}^{AV}$", which can be prevented by using technological production techniques and providing improvements during the operation of the system.
- The exergy destruction, which cannot be prevented due to technological and operation constraints, is called unavoidable exergy destruction "$\dot{E}x_{D,k}^{UN}$".

For a better understanding of the above approaches, the splitting the exergy destruction rate for the *k*th component is demonstrated in Figure 3.2 [8].

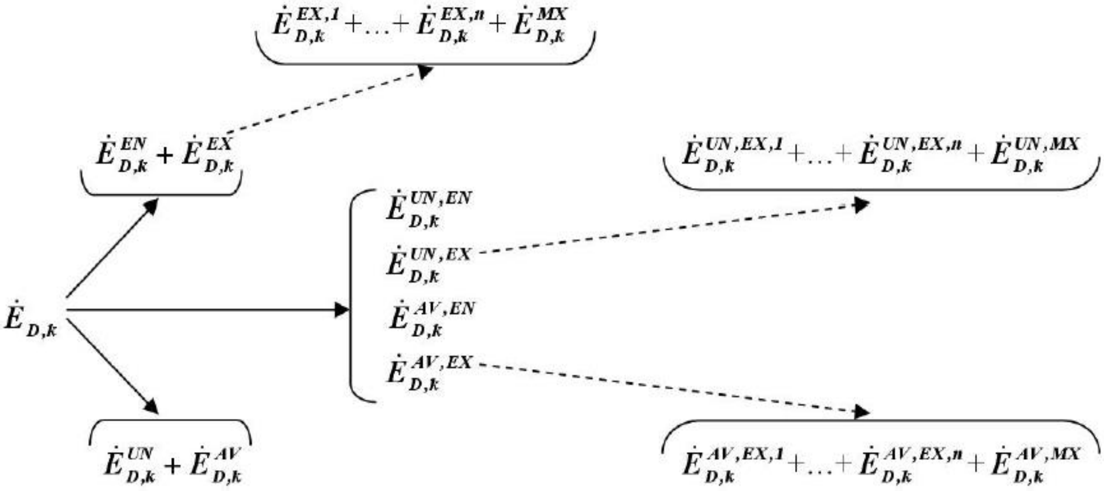


Figure 3.2. Splitting the exergy destruction into avoidable, unavoidable, endogenous and exogenous parts

3.5.1. Endogenous and exogenous exergy destruction

In order to calculate the endogenous exergy destruction "$\dot{E}x_{D,k}^{EN}$" of the *k*th component in a system, the operating conditions of the *k*th component are considered the same as in the real operating conditions and the other system components are assumed to operate at maximum efficiency (theoretical). That is, the temperature, pressure and mass flows of all materials in the inlet-outlet flows are rearranged. Accordingly, exergy destruction rate "$\dot{E}x_{D,k}$" in the component gives the endogenous exergy destruction rate "$\dot{E}x_{D,k}^{EN}$" of that component [45].

Exogenous exergy destruction “$\dot{E}x_{D,k}^{EX}$” is obtained by subtracting the endogenous exergy destruction “$\dot{E}x_{D,k}^{EN}$” from exergy destruction “$\dot{E}x_{D,k}$” in experimental (real) conditions.

$$\dot{E}x_{D,k} = \dot{E}x_{D,k}^{EN} + \dot{E}x_{D,k}^{EX} \tag{3.84}$$

The results of this section enable us to obtain detailed information about the interactions between components, helping to make accurate structural optimization at maximum efficiency.

3.5.2. Avoidable-unavoidable exergy destruction

In the avoidable and unavoidable exergy destruction calculation of a component of the system, the unavoidable exergy destruction “$\dot{E}x_{D,k}^{UN}$” is first calculated. The avoidable exergy destruction “$\dot{E}x_{D,k}^{AV}$” is obtained by subtracting the unavoidable exergy destruction rate from the total exergy destruction rate of the component. In this calculation, the technical and economical conditions that cannot be reached in the future are defined for each component, acceptances are realized and the unavoidable exergy destruction rate is determined. In other words, in order to calculate the unavoidable exergy destruction rate, the calculation is made by assuming that the components in the system operate at maximum efficiency compared to today's technology. While making these calculations, each component is considered separate and isolated from the system. Considering the conditions described above, the unavoidable exergy rate is obtained by multiplying the coefficient determined as the unavoidability ratio and the real product exergy rate [9].

$$\dot{E}x_{D,k}^{UN} = \dot{E}x_{P,k}\left(\frac{\dot{E}x_{D,k}}{\dot{E}x_{P,k}}\right)^{UN} \tag{3.85}$$

The avoidable exergy destruction rate “$\dot{E}x_{D,k}^{AV}$”can be calculated as follows:

$$\dot{E}x_{D,k}^{AV} = \dot{E}x_{D,k} - \dot{E}x_{D,k}^{UN} \tag{3.86}$$

3.5.3. Combination of avoidable/unavoidable exergy destruction with endogenous/exogenous exergy destruction

By combining the concepts of endogenous-exogenous exergy destruction and avoidable-unavoidable exergy destruction, exergy destruction of the *k*th component is divided into four different parts [33,46]:

- The unavoidable part of the endogenous exergy destruction rate of the *k*th component due to technical limitations is defined as unavoidable endogenous exergy destruction rate "$\dot{E}x_{D,k}^{UN,EN}$" and is calculated as follows;

$$\dot{E}x_{D,k}^{UN,EN} = \dot{E}x_{P,k}^{EN}\left(\frac{\dot{E}x_{D,k}}{\dot{E}x_{P,k}}\right)^{UN} \tag{3.87}$$

- The unavoidable exogenous exergy destruction rate of the kth "$\dot{E}x_{D,k}^{UN,EX}$" component is the part that cannot be reduced due to technical limitations in other components and is determined as follows;

$$\dot{E}x_{D,k}^{UN,EX} = \dot{E}x_{D,k}^{UN} - \dot{E}x_{D,k}^{UN,EN} \tag{3.88}$$

- The avoidable endogenous exergy destruction rate of the *k*th component "$\dot{E}x_{D,k}^{AV,EN}$" can be improved again by improving the *k*th component. the endogenous exergy destruction rate "$\dot{E}x_{D,k}^{AV,EN}$" can be expressed as follows;

$$\dot{E}x_{D,k}^{AV,EN} = \dot{E}x_{D,k}^{EN} - \dot{E}x_{D,k}^{UN,EN} \tag{3.89}$$

- The avoidable exogenous exergy destruction rate of the *k*th component "$\dot{E}x_{D,k}^{AV,EX}$" can be reduced by improving the structure of the whole system, increasing the efficiency of other components and increasing the efficiency of the *k*th component. Also the avoidable exogenous exergy destruction rate of the *k*th "$\dot{E}x_{D,k}^{AV,EX}$" component can be calculated as;

$$\dot{E}x_{D,k}^{AV,EX} = \dot{E}x_{D,k}^{AV} - \dot{E}x_{D,k}^{AV,EN} \tag{3.90}$$

3.5.4. System performance parameters obtained from advanced exergetic values

The advanced exergy performance parameters calculated to evaluate each component in detail using the values obtained by breaking down the exergy destruction are shown below;

- A modified exergy efficiency "$\varepsilon_{modified,k}$" [47-49].

$$\varepsilon_{mod,k} = \frac{\dot{Ex}_{P,k}}{\dot{Ex}_{F,k} - \dot{Ex}_{D,k}^{UN} - \dot{Ex}_{D,k}^{AV,EX}} \tag{3.91}$$

- In order to determine the effect of increasing the efficiency of any *k*th component on the whole system, the ratio of avoidable exergy destruction rate of *k*th component to the exergy destruction ratio of the system "$y_{D,k}^{AV,EN}$" can be used [48-49].

$$y_{D,k}^{AV,EN} = \frac{\dot{Ex}_{D,k}^{AV,EN}}{\dot{Ex}_{D,total}} \tag{3.92}$$

- Considering that the *k*th component is isolated from the system, its improvement potential $x_{D,k}^{AV}$ can be determined as follows [50]:

$$x_{D,k}^{AV} = \frac{\dot{Ex}_{D,k}^{AV}}{\dot{Ex}_{D,k}} \tag{3.93}$$

3.6. Advanced Exergoeconomic Analysis

In advanced exergy analysis, convectional exergy destruction ratios obtained by the SPECO method are separated as avoidable-unavoidable (*UN-AV*) and endogenous-exogenous (*EN-EX*). In the advanced exergoeconomic analysis, as in the exergoeconomic analysis, the cost stream values "$\dot{C}_k$" obtained from the exergoeconomic analysis are associated with the advanced exergy destruction flow rate, resulting in the avoidable-unavoidable and endogenous-exogenous parts of the cost of the exergy stream. In addition to the cost of the exergy stream, capital cost "$\dot{Z}_k$" values are also divided into the avoidable-unavoidable and endogenous-exogenous parts within the comprehension of this analysis [48].

The results of the advanced exergoeconomic analysis are evaluated with advanced exergoeconomic factors ($f_k^{AV,EN}$);

$$f_k^{AV,EN} = \frac{\dot{Z}_k^{AV,EN}}{\dot{Z}_k^{AV,EN} + \dot{C}_{D,k}^{AV,EN}} \tag{3.94}$$

The EXCEM method, another exergoeconomic method, will be developed for the first time in this study and applied to the system. In this method called "Advanced EXCEM", it is calculated by passing the following steps;

- Advanced exergy destruction rates are calculated instead of the exergy destruction rate used in the exergoeconomic parameter calculation.
- The investment cost rates of components are determined.
- The rate of exergy destruction parts to capital costs is calculated under the same conditions.

$$\dot{R}_{ex,D,k} = \dot{R}_{ex,D,k}^{EN} + \dot{R}_{ex,D,k}^{EX} \tag{3.95}$$

$$\dot{R}_{ex,D,k} = \dot{R}_{ex,D,k}^{UN} + \dot{R}_{ex,D,k}^{AV} \tag{3.96}$$

$$\dot{R}_{ex,D,k} = \dot{R}_{ex,D,k}^{UN,EN} + \dot{R}_{ex,D,k}^{UN,EX} + \dot{R}_{ex,D,k}^{AV,EN} + \dot{R}_{ex,D,k}^{AV,EX} \tag{3.97}$$

The equations obtained by associating exergoeconomic analysis results with advanced exergy analysis results are shown in the Table 3.3 [46-51].

Table 3.3. Cost and investment cost equations of exergy destruction fractions

Terms	**Investment cost “$\dot{Z}_k$” of *k*th component**	**Cost rate “$\dot{C}_{D,k}$” of *k*th component**	**The advanced exergoeconomic parameter “$\dot{R}_{ex,D}$” of *k*th component (Advanced EXCEM)**
$(\dot{Z}_k^{EN}, \dot{C}_{D,k}^{EN}, \dot{R}_{ex,k}^{EN})$	Endogenous investment cost rates $\dot{Z}_k^{EN} = \dot{Ex}_{P,k}^{EN} \left(\frac{\dot{Z}}{\dot{Ex}_P}\right)_k^{real}$ (3.98)	Endogenous exergy destruction cost rate $\dot{C}_{D,k}^{EN} = c_{F,k} \dot{Ex}_{D,k}^{EN}$ (3.99)	Endogenous exergoeconomic parameter $\dot{R}_{ex,D,k}^{EN} = \frac{\dot{Ex}_{D,k}^{EN}}{\dot{Z}_k}$ (3.100)
$(\dot{Z}_k^{EX}, \dot{C}_{D,k}^{EX}, \dot{R}_{ex,k}^{EX})$	Exogenous investment cost rates $\dot{Z}_k^{EX} = \dot{Z}_k - \dot{Z}_k^{EN}$ (3.101)	Exogenous exergy destruction cost rate $\dot{C}_{D,k}^{EX} = \dot{C}_{D,k} - \dot{C}_{D,k}^{EN}$ (3.102)	Exogenous exergoeconomic parameter $\dot{R}_{ex,D,k}^{EX} = \frac{\dot{Ex}_{D,k}^{EX}}{\dot{Z}_k}$ (3.103)
$(\dot{Z}_k^{UN}, \dot{C}_{D,k}^{UN}, \dot{R}_{ex,k}^{UN})$	Unavoidable investment cost rates $\dot{Z}_k^{UN} = \dot{Ex}_{P,k} \left(\frac{\dot{Z}}{\dot{Ex}_P}\right)_k^{UN}$ (3.104)	Unavoidable exergy destruction cost rate $\dot{C}_{D,k}^{UN} = c_{F,k} \dot{Ex}_{D,k}^{UN}$ (3.105)	Unavoidable exergoeconomic parameter $\dot{R}_{ex,D,k}^{UN} = \frac{\dot{Ex}_{D,k}^{UN}}{\dot{Z}_k}$ (3.106)
$(\dot{Z}_k^{AV}, \dot{C}_k^{AV}, \dot{R}_{ex,k}^{AV})$	Avoidable investment cost rates $\dot{Z}_k^{AV} = \dot{Z}_k - \dot{Z}_k^{UN}$ (3.107)	Avoidable exergy destruction cos $\dot{C}_{D,k}^{AV} = \dot{C}_{D,k} - \dot{C}_{D,k}^{UN}$ (3.108)	Avoidable exergoeconomic parameter $\dot{R}_{ex,D,k}^{AV} = \frac{\dot{Ex}_{D,k}^{AV}}{\dot{Z}_k}$ (3.109)
$(\dot{Z}_k^{UN,EN}, \dot{C}_{D,k}^{UN,EN}, \dot{R}_{ex,k}^{UN,EN})$	Unavoidable endogenous investment cost rates $\dot{Z}_k^{UN,EN} = \dot{Ex}_{P,k}^{EN} \left(\frac{\dot{Z}}{\dot{Ex}_P}\right)_k^{UN}$ (3.110)	Unavoidable endogenous exergy destruction cost rate $\dot{C}_{D,k}^{UN,EN} = c_{F,k} \dot{Ex}_{D,k}^{UN,EN}$ (3.111)	Unavoidable endogenous exergoeconomic parameter $\dot{R}_{ex,D,k}^{UN,EN} = \frac{\dot{Ex}_{D,k}^{UN,EN}}{\dot{Z}_k}$ (3.112)
$(\dot{Z}_k^{UN,EX}, \dot{C}_{D,k}^{UN,EX}, \dot{R}_{ex,k}^{UN,EX})$	Unavoidable exogenous investment cost rates $\dot{Z}_k^{UN,EX} = \dot{Z}_k^{UN} - \dot{Z}_k^{UN,EN}$ (3.113)	Unavoidable exogenous exergy destruction cost rate $\dot{C}_{D,k}^{UN,EX} = \dot{C}_{D,k}^{UN} - \dot{C}_{D,k}^{UN,EN}$ (3.114)	Unavoidable exogenous exergoeconomic parameter $\dot{R}_{ex,D,k}^{UN,EN} = \frac{\dot{Ex}_{D,k}^{UN,EN}}{\dot{Z}_k}$ (3.115)
$(\dot{Z}_k^{AV,EN}, \dot{C}_{D,k}^{AV,EN}, \dot{R}_{ex,k}^{AV,EN})$	Avoidable endogenous investment cost rates $\dot{Z}_k^{AV,EN} = \dot{Z}_k^{EN} - \dot{Z}_k^{UN,EN}$ (3.116)	Avoidable endogenous exergy destruction cost rate $\dot{C}_{D,k}^{AV,EN} = \dot{C}_{D,k}^{EN} - \dot{C}_{D,k}^{UN,EN}$ (3.117)	Avoidable endogenous exergoeconomic parameter $\dot{R}_{ex,D,k}^{AV,EN} = \frac{\dot{Ex}_{D,k}^{AV,EN}}{\dot{Z}_k}$ (3.118)
$(\dot{Z}_k^{AV,EX}, \dot{C}_{D,k}^{AV,EX}, \dot{R}_{ex,k}^{AV,EX})$	Avoidable exogenous investment cost rates $\dot{Z}_k^{AV,EX} = \dot{Z}_k^{EX} - \dot{Z}_k^{UN,EX}$ (3.119)	Avoidable endogenous exergy destruction cost rate $\dot{C}_{D,k}^{AV,EX} = \dot{C}_{D,k}^{EX} - \dot{C}_{D,k}^{UN,EX}$ (3.120)	Avoidable endogenous exergoeconomic parameter $\dot{R}_{ex,D,k}^{AV,EX} = \frac{\dot{Ex}_{D,k}^{AV,EX}}{\dot{Z}_k}$ (3.121)

3.7. Advanced Exergoenvironmental Analysis

In advanced exergoenvironmental analysis such as advanced exergoeconomic analysis, it is associated with destruction parts obtained from advanced exergy analysis, allowing us to better understand the environmental impact of the components. Due to technological and economic constraints, the environmental impact of the non-degradable part of the exergy stream is defined as unavoidable environmental impact, while the remainder of the environmental impact is defined as avoidable environmental impact. The endogenous and exogenous exergy destructions, which reveal the relationships and effects of the components, are associated with the environmental impact and endogenous and exogenous environmental effects are determined. The equations obtained by associating exergoenvironmental analysis results with advanced exergy analysis results are shown in the Table 3.4 [44,52].

Table 3.4. Environmental impacts equations of exergy destruction fractions

Terms	**Environmental impact rate of material stream "$\dot{B}_{D,k}$" associated with the exergy destruction (GJ/h)**	
Endogenous environmental impact rate $(\dot{B}^{EN}_{D,k})$	$\dot{B}^{EN}_{D,k} = b_{F,k}\dot{E}x^{EN}_{D,k}$	(3.122)
Exogenous environmental impact rate $(\dot{B}^{EX}_{D,k})$	$\dot{B}^{EX}_{D,k} = \dot{B}_{D,k} - \dot{B}^{EN}_{D,k}$	(3.123)
Unavoidable environmental impact rate $(\dot{B}^{UN}_{D,k})$	$\dot{B}^{UN}_{D,k} = b_{F,k}\dot{E}x^{UN}_{D,k}$	(3.124)
Avoidable environmental impact rate $(\dot{B}^{AV}_{D,k})$	$\dot{B}^{AV}_{D,k} = \dot{B}_{D,k} - \dot{B}^{UN}_{D,k}$	(3.125)
Unavoidable endogenous environmental rate $(\dot{B}^{UN,EN}_{D,k})$	$\dot{B}^{UN,EN}_{D,k} = b_{F,k}\dot{E}x^{UN,EN}_{D,k}$	(3.126)
Unavoidable exogenous environmental impact rate $(\dot{B}^{UN,EX}_{D,k})$	$\dot{B}^{UN,EX}_{D,k} = \dot{B}^{UN}_{D,k} - B^{UN,EN}_{D,k}$	(3.127)
Avoidable endogenous environmental impact rate $(\dot{B}^{AV,EN}_{D,k})$	$\dot{B}^{AV,EN}_{D,k} = \dot{B}^{EN}_{D,k} - \dot{B}^{UN,EN}_{D,k}$	(3.128)
Avoidable exogenous environmental impact rate $(\dot{B}^{AV,EX}_{D,k})$	$\dot{B}^{AV,EX}_{D,k} = \dot{B}^{EN}_{D,k} - \dot{B}^{AV,EN}_{D,k}$	(3.129)

3.8. Economic Assessment

It is very important for any firm to evaluate the investment financially and choose the most suitable project in line with strategic plans before making an investment decision. These projects often include upgrading the existing machine, increasing capacity, efficiency projects or setting up a factory. Before the investment decision is made, the time (period) of that investment to profit, the monetary return of the investment and the maximum benefit it can provide can be understood by financial analysis methods. Net Present Value (NPV) method, which is one of these methods, can provide both understandable, easy and realistic results. This method, which is used by many financial analysts, is a method that takes the future value of money into account by reducing the future cash flows to a certain discount rate. In other words, it refers to the difference obtained by deducting the present value of the investment expenses from the present value of the return on the economic life of the investment. "NPV" is calculated as follows [53-55];

$$NPV = \sum_{t=1}^{n} \frac{R_t}{\mathrm{a_t}} - C_0 \tag{3.130}$$

$$\mathrm{a_t} = \frac{1}{(1+r)^t} \tag{3.131}$$

$$R_t = A_t - B_t \tag{3.132}$$

where "n" is the life of the project in years, "t" is the time of cash flow, "R_t" is cash flow in year ($), "$r$" is discount rate (represent the interest rate), "C_0" is the capital cost or investment cost ($), "$A_t$" is benefit per year ($/year) and "B_t" is expenditure per year ($/year). NPV method is shown in Figure 3.3 [56]. According to the results of the NPV method;

- The positive of NPV shows that it is a profitable project. In other words, it is understood that the return to be provided by the investment is higher than the capital cost paid for the investment.
- With the help of the NPV method, the total earnings are calculated over the economic life of the investment.
- It determines the period when the investment makes a profit.

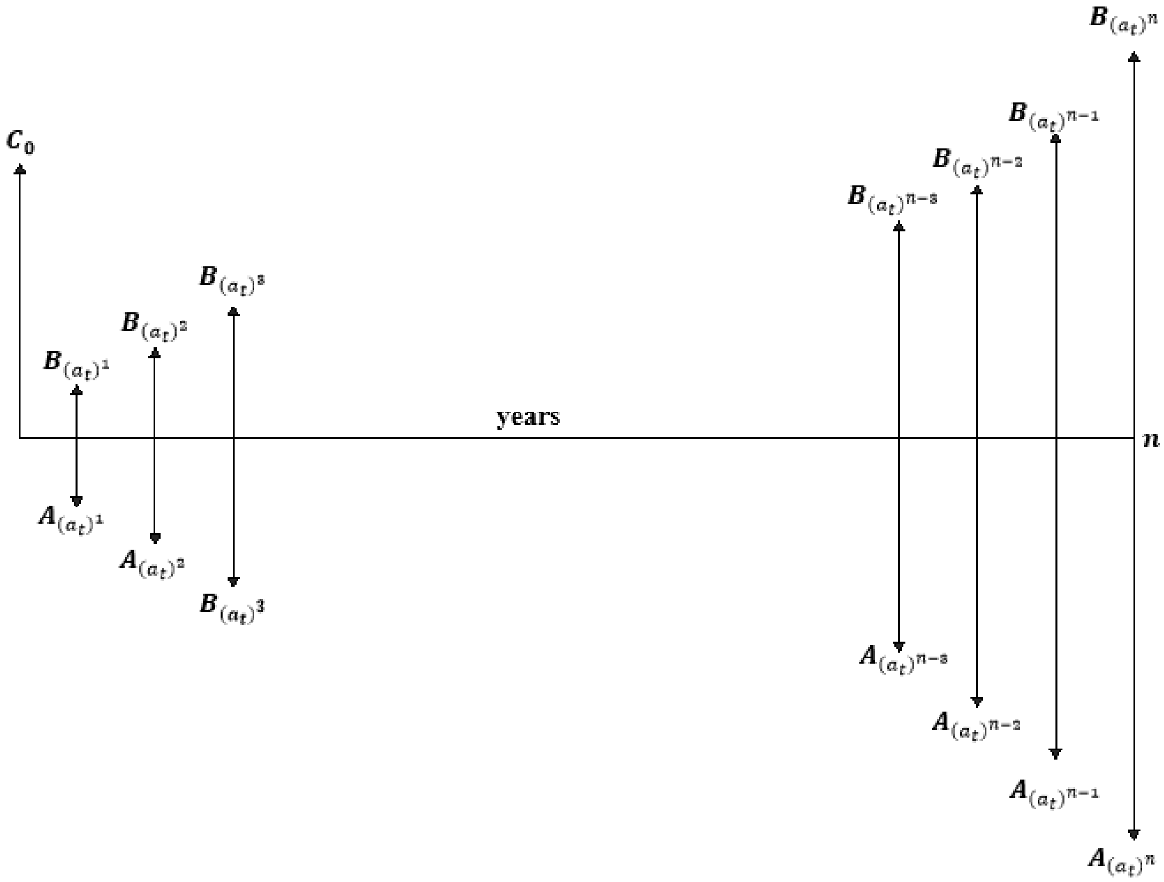


Figure 3.3. NPV flow diagram

4. COGENERATION APPLICATION FOR CERAMIC PLANT

4.1. System Description

Cogeneration system has been designed by using a gas turbine for the ceramic plant located in the Uşak Industry Estate Zone in Turkey, the exergy and advanced exergy analysis have been made for this system and thermodynamically investigated, besides all this system has been economically evaluated. There are five different production lines in this factory, which mainly produces two different types of ceramics as ground and wall tiles. The ground tiles are produced in three of these production lines and wall tiles in two of them. The factory, where especially the firing and drying processes are intense, has three kilns for ground tiles in these production lines, while there are four kilns (two double-decked) for the wall tile production line. In addition, spray dryers with 4000 kg/h and 8000 kg/h water evaporation capacities are available for each wall and ground tiles production lines, respectively. The wall tile dryer (WD) and ground tile dryer (GD) examined in this study is one of the important components of the cogeneration system.

In spray dryers, the heat required to evaporate the water in the sludge is given in the form of combustion gases or heated air. This heat comes into contact with water droplets and provides evaporation by convection. This is the type of spray dryer commonly used in the ceramic industry. All processes of the spray dryer given in Figure 4.1 are shown in detail;

- The sludge obtained by grinding raw materials into aqueous solutions is transported to the sprayers of the spray dryers with the help of pumps (1) (22-28 bars).
- Filters (2) are used to prevent clogging of the nozzle, which allows mud to be sprayed inside (4) the spray dryer.
- The distributor ring (3) is the part on which the nozzles are mounted.
- The air taken from the environment with the help of fan (7) is heated by burning natural gas in the combustion chamber (8) and a hot air stream is created 550-600°C. This hot air stream is carried to the air distributor part (10) of the spray dryer with the help of pipes (9). The air required for the combustion air is defined as primary air and the air required for the hot air flow is defined as secondary air.

- The hot air stream in the air distributor is directed downward in the form of vortex, and heat exchange occurs by encountering slurry sprayed into the spray dryer. The sludge, which loses water in it, becomes granular called masse in the ceramic industry and discharged from the exit chamber (5) of the spray dryer. The steam generated during this process is released out of the chimney (13). Also, residual fine dust suspended in the air is collected by the fan (11) and collected in cyclones (6) [57].

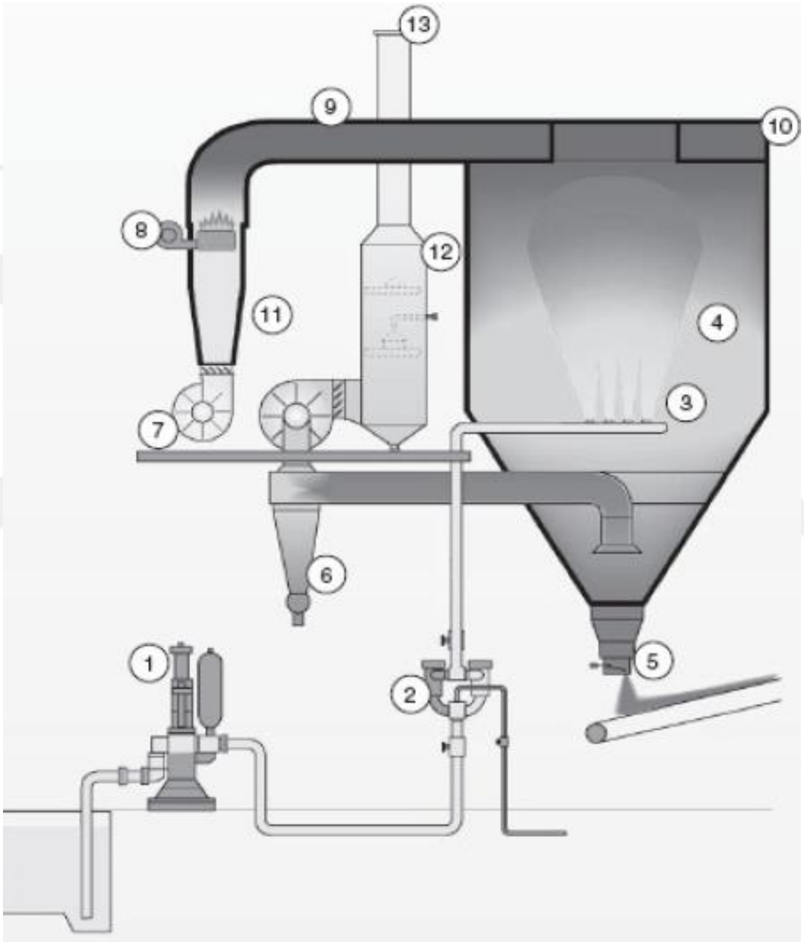


Figure 4.1. Schematic of the spray dryers

In this ceramic factory, a waste heat recovery system is installed for spray dryers. The cooling air of 177 °C and 168 °C, obtained from the kilns of the wall and floor tile production lines, is used instead of the primary and secondary air received by spray dryers from the ambient. In other words, the cooling air of the kilns is used as preheating in WD and GD. Thus, instead of increasing the ambient air between 10°C and 30°C to 550°C-600°C in the combustion chamber, the system increases the cooling air from 160°C-170°C to 550°C-

600°C, resulting in less natural gas consumption. Thus, energy savings are reduced by saving energy. For a better understanding of spray dryers, its energy and mass balance is shown in Figure 4.2 [57].

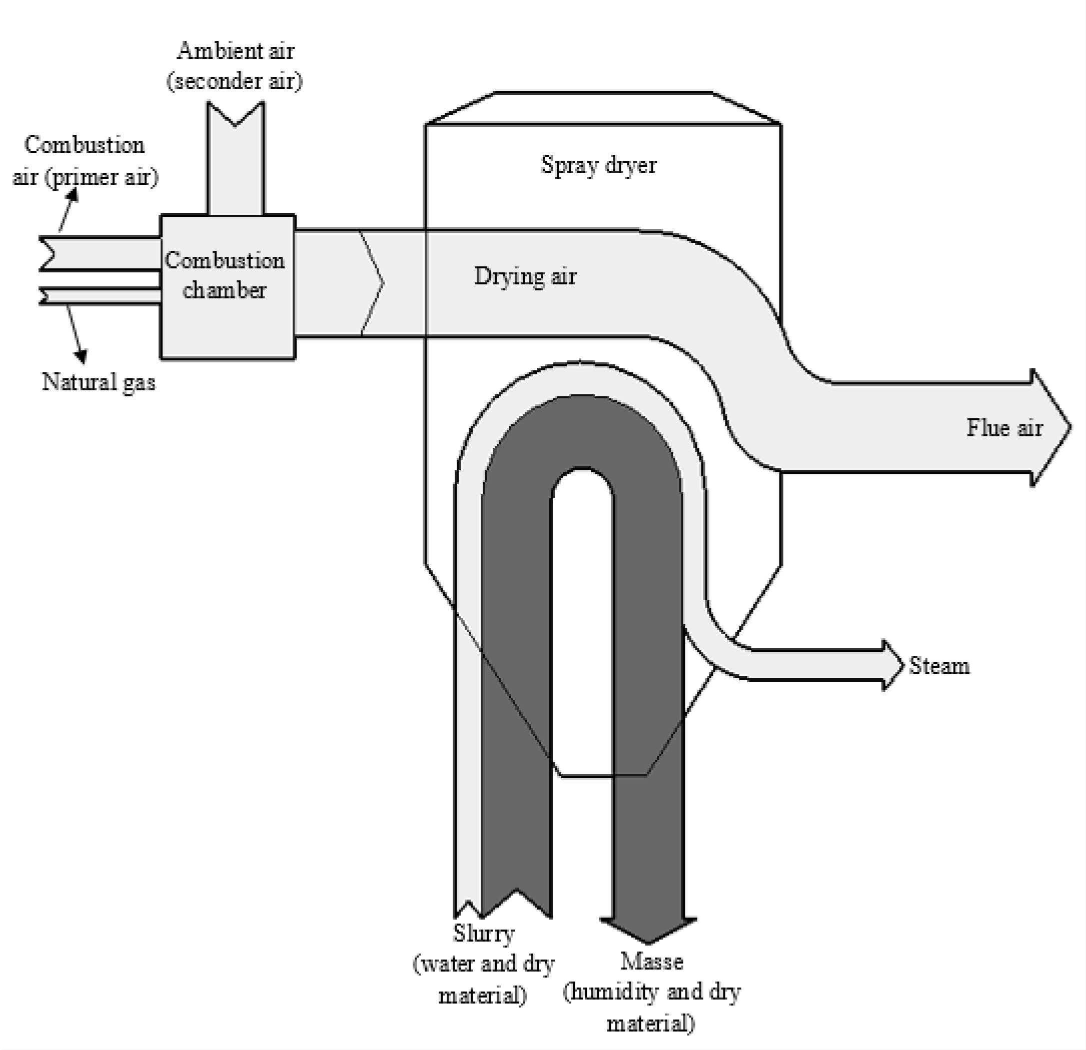


Figure 4.2. Energy and mass balance in the spray dryer

The highest cost element of ceramic factories with heat intensive processes is the energy with a ratio of 35% to 40% of the total industrial cost. Therefore, energy management is the most important department in these factories. In addition to the cost element of energy, it also affects the production efficiency in the processes in case of any power outages or fluctuations. Especially the increase in electricity costs, power cuts and power fluctuations cause the following problems in the factory;

- Continuously increasing electricity costs reduce the ability to compete in global markets.

- Due to continuous power cuts, quality and capacity loss occur in production.
- As a result of any power outage, too many discarded products are exposed.
- There are problems in machinery and equipment due to sudden electrical fluctuations.
- In addition, due to the loss of quality, customer complaints increase, causing the brand to lose its value.

In order to prevent the above-mentioned results, that is, it has been proposed to establish a cogeneration system (COGEN) with gas turbine for the continuity of production with maximum quality and capacity by providing an uninterrupted electrical energy. The electricity consumption (installed power) of this ceramic plant ranges from 3.8 MW to 4.2 MW. Therefore, Centaur 50 Gas Turbine Generator which shown Figure 4.3, is suggested. The general specifications of the gas turbine unit is presented in Table 4.1.

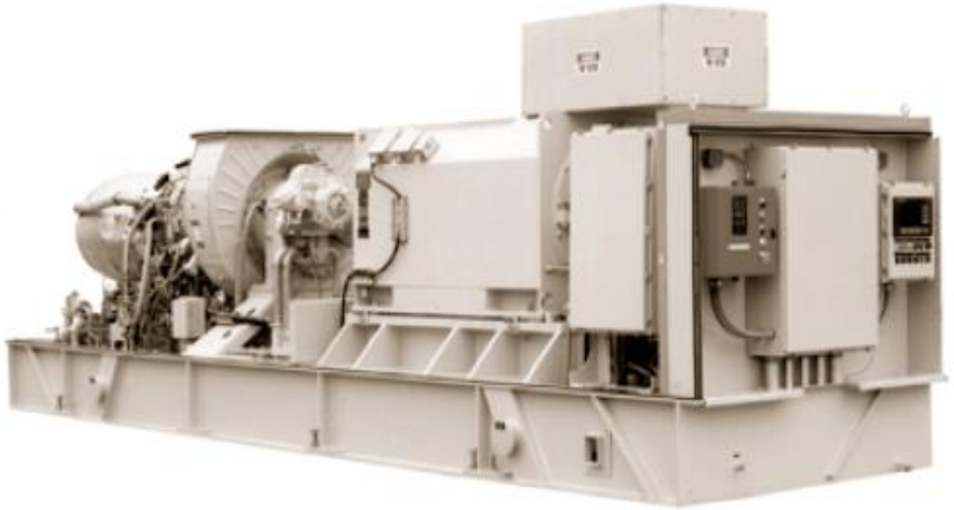


Figure 4.3. General view of the Centaur 50 Gas Turbine Generator

Table 4.1. General specifications of the gas turbine unit

Performance	
Output Power	4.6 MW
Exhaust Flow	68680 kg/h
Heat Rate	12270 kJ/kWh
Exhaust Temperature	510°C
Engine Efficiency	29.3%
Pressure Ratio	10.6:1

Also, since exhaust gas released from the gas turbine unit can be used in spray dryers, there is no need for a new heat process design. The exhaust gas released is sufficient for all of the drying air required for the WD (secondary air) and is sufficient for most of the GD. The general schematic layout of the COGEN is given in Figure 4.4. The COGEN system consists of air compressor (AC), combustion chamber (CC), gas turbine (GT), pipe line (PL), wall tile dryer (WD), ground tile dryer (GD), electrical generator, three fans (Fan_1, Fan_2, Fan_3 and Fan_4) and four pressure reducing valves.

Some of the assumptions of COGEN modeled for the ceramic industry in energy and exergy calculations are shown below;

- The COGEN operates under steady state and steady flow conditions.
- The combustion reaction is considered as a complete combustion (stoichiometric combustion).
- The kinetic and potential energies of the materials entering and leaving the control volume are neglected.
- The exhaust gas, natural gas, combustion gas and flue gas are considered as ideal gas mixtures.
- Electric energy used in pumps and fans are not included in the calculations because they are very few compared to other energy elements.
- In the piping line used to transport exhaust gases to spray dryers, pressure loss is neglected.
- In order to make the analysis simpler, spray dryer unit is considered as a single component that includes the combustion chamber and slurry pumps, the main body of spray dryers. In addition, it is assumed that all the power produced in the gas turbine unit is converted into electrical energy. Thus, the energy efficiency in the electricity generator has been accepted as 100%.
- The energy losses due to friction are neglected.
- The dead state (reference) temperatures are assumed to be 10°C, 15°C, 20°C, 25°C and 30°C to assess the system under various conditions.
- The mass flow rate is considered equal for each the dead state (reference) temperatures.

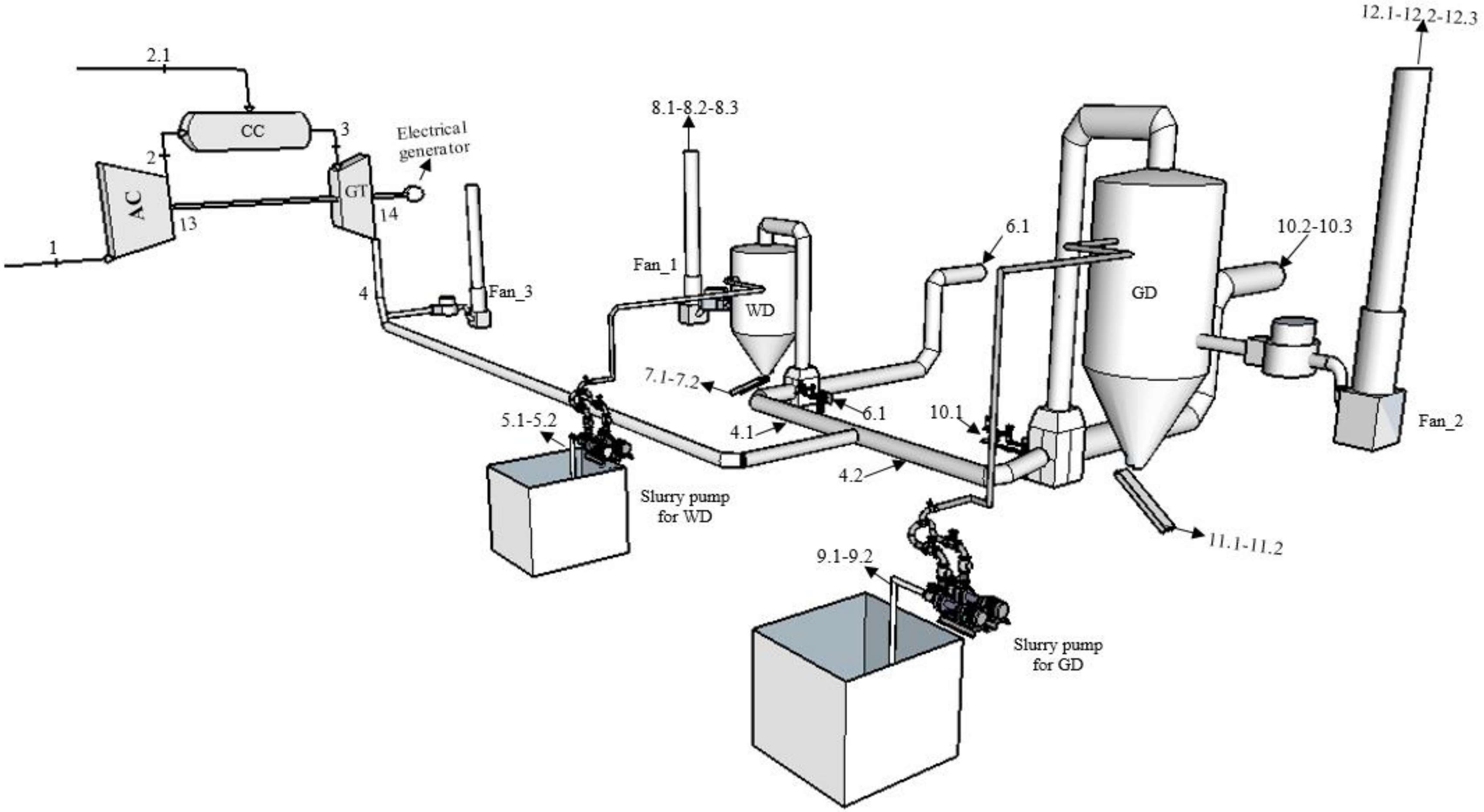


Figure 4.4. General schematic layout of the COGEN

- The isentropic efficiencies of air compressors and gas turbine in the gas turbine unit accepted as adiabatic process are assumed to be 82% and 87%, respectively.
- Since the temperature of the system boundaries is considered to be equal to the temperature of the reference environment "T_0", it is assumed that there is no loss of exergy in all components.
- In order to evaluate the seasonal temperature changes in the ceramic industry affecting energy consumption and to assess the COGEN under various conditions, the dead state (reference) temperatures are accepted as 10°C, 15°C, 20°C, 25°C and 30°C and the results are compared.

The mass flow rate, temperature, pressure and energy flow rates of the materials entering and leaving COGEN are presented in Table 4.2.

Table 4.2. Specifications and energy rates of the materials

State no.	**Fluid Type**	**Mass flow rate $\dot{m}$ (kg/s)**	***T* (°C)**	***P* (kPa)**	**Energy rate (kW)**
1	Ambient air	18.805	30	101.325	5829.915
2	Compressed air	18.805	388.88	1063.913	13542.315
2.1	Fuel	0.432	30	1515	20570.597
3	Combustion gas	19.237	956.08	1010.717	29668.116
4	Exhaust gas	19.237	510	106.391	17555.734
4.1	Exhaust gas for WD	7.43	489	106.391	6571.986
5.1	Dry materials of slurry	2.48	43.3	101.325	609.588
5.2	Water in slurry	1.395	43.3	101.325	1854.054
6.1	Fuel	0.0244	30	1515	1163.987
6.2	Combustion gas	1.02	172	101.325	477.022
7.1	Masse (dry)	2.48	50	2026.5	629.443
7.2	Humidity of masse	0.158	50	2026.5	215.181
8.1	Water vapor	1.237	96	101.325	3306.426
8.2	Combustion flue gas	1.045	96	101.325	416.289
8.3	Other flue gas	7.43	96	101.325	2913.212
4.2	Exhaust gas for GD	11.807	489	106.391	10444.065
9.1	Dry materials of Slurry	4.622	45.3	101.325	1142.938
9.2	Water in slurry	2.6	45.3	101.325	3476.228
10.1	Fuel	0.028	30	1515	1335.940
10.2	Combustion gas	1.171	172	101.325	553.373
10.3	Flue gas	4.222	172	101.325	1994.775
11.1	Masse (dry)	4.622	51.3	2026.5	1176.742
11.2	Humidity of masse	0.295	51.3	2026.5	402.281
12.1	Water vapor	2.305	99	101.325	6161.352
12.2	Combustion flue gas	1.297	99	101.325	481.866
12.3	Other flue gas	15.932	99	101.325	6363.170
13	Compressor work				7712.400
14	Turbine net work				4400

The specifications of the ambient air and natural gas are illustrated in Table 4.3 and Table 4.4, respectively, by using some of Ref. [22] data.

Table 4.3. Specifications of the ambient air at 30°C

Chemical formula	**Contents**	**Volumetric ratio (%)**	**Mass ratio (%)**	c_p **(kJ/kgK)**
N_2	Nitrogen	77.48	75.75	1.049
O_2	Oxygen	20.59	23.01	0.956
H_2O (g)	Water (gas)	1.9	1.19	0.978
CO_2	Carbon dioxide	0.03	0.05	1.927

Table 4.4. Specifications of the natural gas at 30°C

Chemical formula	**Contents**	**Volumetric ratio (%)**	**Mass ratio (%)**	***LHV*** **(kJ/kg)**	γ_f	c_p **(kJ/kgK)**
CH_4	Methane	91.94	84.44	50050	1.0308	2.204
C_2H_6	Ethane	3.53	6.08	47520	1.0488	1.779
C_3H_8	Propane	0.90	2.27	46340	1.0548	1.715
C_4H_{10}	Butane	0.38	1.26	45370	1.0578	1.727
C_5H_{12}	Pentane	0.11	0.45	44910	1.0596	1.715
N_2	Nitrogen	2.66	4.26			1.04
CO_2	Carbon dioxide	0.48	1.21			0.853

The air/fuel ratio is calculated for the CC, WD and GD as follows [22-24]:

$$\frac{\dot{m}_{air}}{M_{air}} \Bigg/ \frac{\dot{m}_{fuel}}{M_{fuel}} = \lambda \tag{4.1}$$

$$\left(\frac{\frac{\dot{m}_{N_2}}{M_{N_2}} + \frac{\dot{m}_{CO_2}}{M_{CO_2}} + \frac{\dot{m}_{H_2O}}{M_{H_2O}} + \frac{\dot{m}_{O_2}}{M_{O_2}}}{\frac{\dot{m}_{CH_4}}{M_{CH_4}} + \frac{\dot{m}_{C_2H_4}}{M_{C_2H_4}} + \frac{\dot{m}_{C_3H_8}}{M_{C_3H_8}} + \frac{\dot{m}_{C_4H_{10}}}{M_{C_4H_{10}}} + \frac{\dot{m}_{C_5H_{12}}}{M_{C_5H_{12}}} + \frac{\dot{m}_{N_2}}{M_{N_2}} + \frac{\dot{m}_{CO_2}}{M_{CO_2}}} \right) = \lambda \tag{4.2}$$

where "λ" is the air/fuel molar ratio, which is calculated as 26.480 for CC, 41.902 for WD and GD. This ratio can be written in the combustion reaction equation as follows;

$$(0.9194CH_4 + 0.0353C_2H_6 + 0.009C_3H_8 + 0.0038C_4H_{10} + 0.011C_5H_{12} + 0.026N_2 + 0.0048CO_2) + \lambda(0.2059O_2 + 0.7748N_2 + 0.019H_2O + 0.0003CO_2) \Rightarrow (xO_2 + yN_2 + zH_2O + wCO_2) \tag{4.3}$$

The molecular and mass distribution rates of the products obtained as a result of combustion reactions in CC, WD and GD are described in Table 4.5.

Table 4.5. The molecular and mass distribution rate of the products of combustion reactions

Chemical formula	**Contents**	**Exhaust gas of CC**		**Flue gas of GD and WD**	
		Volumetric ratio (%)	**Mass ratio (%)**	**Volumetric ratio (%)**	**Mass ratio (%)**
N_2	Nitrogen	74.663	74.148	74.646	74.191
O_2	Oxygen	12.398	14.072	11.948	13.571
H_2O (g)	Water (gas)	9.12	5.823	9.429	6.024
CO_2	Carbon dioxide	3.818	5.958	3.978	6.213

The molar and mass distribution rates of slurry and masse forming molecules are given in the Table 4.6;

Table 4.6. Molar and mass distribution rates of molecules of slurry and masse

Chemical formula	**Contents**	**Volumetric ratio (%)**	**Mass ratio (%)**
Na_2O	Di Sodium Oxide	1.79%	1.71%
CaO	Calcium Oxide	11.87%	10.29%
K_2O	Potassium Oxide	1.28%	1.86%
MgO	Magnesium oxide	1.52%	0.95%
Fe_2O_3	Iron (III) oxide	0.61%	1.50%
TiO_2	Titanium dioxide	0.53%	0.66%
Al_2O_3	Aluminum oxide	9.64%	15.19%
SO_3	Sulfur trioxide	0.88%	1.09%
SiO_2	Silicon dioxide	71.88%	66.75%

4.2. Conventional Exergy Balance Equations of COGEN and Its Components

The cycle of exhaust gas obtained from the gas turbine in the cogeneration system and the numbered other materials entering and leaving the components in this system are shown in Figure 4.4. The exergy values of these materials, the specific properties of which are shown in Table 4.2-4.6, are shown in Table 4.7 for five different dead state temperatures (10-15-20-25-30 °C). In order to establish exergoeconomic and exergoenvironmental balance equations, the exergy analysis of the system must be done first by using exergetic values and exergy balance equations, which is given Table 4.8. Also, the exergy balance for the COGEN is summarized as a Grassmann diagram at Figure 4.5.

Table 4.7. Exergy rates of the materials for five dead states temperatures

Stream no.	**Fluid Type**	**Exergy rate for five dead states temperatures (*kW*)**				
		10 °C	**15 °C**	**20 °C**	**25 °C**	**30 °C**
1	Ambient air	74.923	59.470	41.238	28.853	18.014
2	Compressed air	7029.045	7001.819	6970.134	6945.926	6923.263
2.1	Fuel	21125.355	21127.870	21130.464	21133.135	21135.882
3	Combustion gas	18412.798	18308.947	18199.042	18099.014	18000.617
4	Exhaust gas	5768.259	5652.023	5530.720	5418.192	5307.265
4.1	Exhaust gas for WD	2087.783	2044.041	1998.366	1956.053	1914.359
5.1	Dry materials of slurry	1395.927	1394.945	1394.122	1393.467	1392.973
5.2	Water in slurry	80.385	77.438	74.946	72.954	71.453
6.1	Fuel	1195.365	1195.507	1195.654	1195.805	1196.107
6.2	Combustion gas	53.682	50.914	47.950	45.347	42.828
7.1	Masse (dry)	1397.507	1396.300	1395.262	1394.391	1393.682
7.2	Humidity of masse	9.653	9.241	8.896	8.588	8.346
8.1	Water vapor	784.280	740.940	698.900	654.260	610.920
8.2	Combustion flue gas	13.319	11.212	8.921	7.011	5.188
8.3	Other flue gas	62.125	46.374	29.333	14.908	1.099
4.2	Exhaust gas for GD	3317.863	3248.349	3175.762	3108.520	3042.260
9.1	Dry materials of Slurry	2601.640	2599.689	2598.049	2596.716	2595.684
9.2	Water in slurry	152.178	146.244	141.258	137.202	134.062
10.1	Fuel	1371.953	1372.116	1372.285	1372.458	1372.636
10.2	Combustion gas	59.002	55.673	52.117	48.976	45.932
10.3	Flue gas	229.623	217.920	205.401	194.379	183.702
11.1	Masse (dry)	2604.278	2601.968	2599.973	2598.287	2596.905
11.2	Humidity of masse	18.157	17.367	16.685	16.109	15.637
12.1	Water vapor	1467.430	1386.773	1306.117	1225.460	1144.803
12.2	Combustion flue gas	24.060	21.724	19.176	17.066	15.057
12.3	Other flue gas	310.466	278.524	243.778	214.740	187.032
13	Compressor work	7712.393	7712.393	7712.393	7712.393	7712.393
14	Turbine net work	4400	4400	4400	4400	4400

Table 4.8. Equations of exergy balance and efficiency of the COGEN and its components

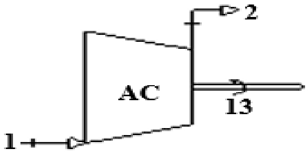
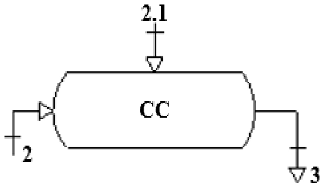
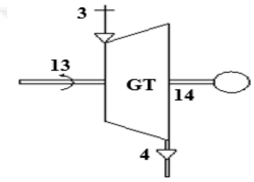
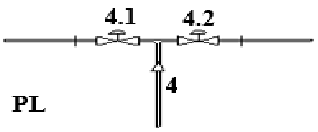
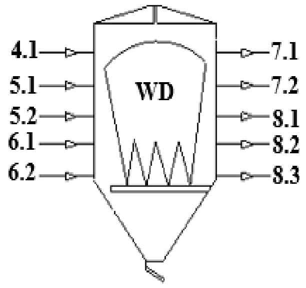
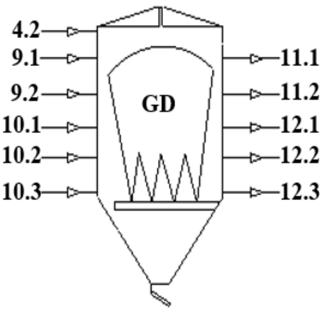
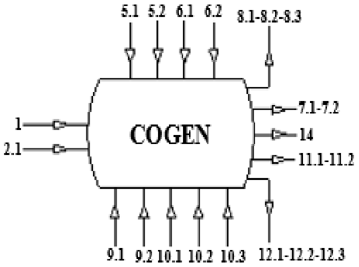
Components (Control Volume)	**Exergy Relations**	**Exergy efficiency equation**
	$\dot{E}_{x,F,AC}=\dot{W}_{13}$ (4.4) $\dot{E}_{xP,AC}=\dot{E}x_2-\dot{E}x_1$ (4.5) $\dot{E}_{xD,AC}=\dot{W}_{13}-(\dot{E}x_2-\dot{E}x_1)$ (4.6)	$\psi_{AC}=\frac{\dot{W}_{13}}{\dot{E}x_2-\dot{E}x_1}$ (4.7)
	$\dot{E}_{x,F,CC}=\dot{E}x_{2.1}$ (4.8) $\dot{E}_{xP,CC}=\dot{E}x_3-\dot{E}x_{2.1}$ (4.9) $\dot{E}_{xD,CC}=\dot{E}x_{2.1}-(\dot{E}x_3-\dot{E}x_2)$ (4.10)	$\psi_{CC}=\frac{(\dot{E}x_3-\dot{E}x_2)}{\dot{E}x_{2.1}}$ (4.11)
	$\dot{E}_{x,F,GT}=\dot{E}x_3-\dot{E}x_4$ (4.12) $\dot{E}_{xP,GT}=\dot{W}_{13}+\dot{W}_{14}$ (4.13) $\dot{E}_{xD,GT}=(\dot{E}x_3-\dot{E}x_4)-(\dot{W}_{13}+\dot{W}_{14})$ (4.14)	$\psi_{GT}=\frac{\dot{W}_{13}+\dot{W}_{14}}{\dot{E}x_2-\dot{E}x_1}$ (4.15)
	$\dot{E}_{x,F,PL}=\dot{E}x_4$ (4.16) $\dot{E}_{xP,PL}=\dot{E}x_{4.1}+\dot{E}x_{4.2}$ (4.17) $\dot{E}_{xD,PL}=\dot{E}x_4-(\dot{E}x_{4.1}+\dot{E}x_{4.2})$ (4.18)	$\psi_{PL}=\frac{\dot{E}x_{4.1}+\dot{E}x_{4.2}}{\dot{E}x_4}$(4.19)
	$\dot{E}_{x,F,WD}=\begin{bmatrix}(\dot{E}x_{4.1}+\dot{E}x_{6.1}+\dot{E}x_{6.2})\\-(\dot{E}x_{8.2}+\dot{E}x_{8.3})\end{bmatrix}$ (4.20) $\dot{E}_{x,P,WD}=\begin{bmatrix}(\dot{E}x_{7.1}+\dot{E}x_{7.2}+\dot{E}x_{8.1})\\-(\dot{E}x_{5.1}+\dot{E}x_{5.2})\end{bmatrix}$ (4.21) $\dot{E}_{xD,WD}=\dot{E}_{x,F,WD}-\dot{E}_{x,P,WD}$ (4.22)	$\psi_{WD}=\frac{\dot{E}_{xP,WD}}{\dot{E}_{xF,WD}}$ (4.23)
	$\dot{E}_{x,F,GD}=$ $\begin{bmatrix}(\dot{E}x_{4.2}+\dot{E}x_{10.1}+\dot{E}x_{10.2}+\dot{E}x_{10.3})\\-(\dot{E}x_{12.2}+\dot{E}x_{12.3})\end{bmatrix}$ (4.24) $\dot{E}_{x,P,GD}=\begin{bmatrix}(\dot{E}x_{11.1}+\dot{E}x_{11.2}+\dot{E}x_{12.1})\\-(\dot{E}x_{9.1}+\dot{E}x_{9.2})\end{bmatrix}$ (4.25) $\dot{E}_{xD,WD}=\dot{E}_{x,F,WD}-\dot{E}_{x,P,WD}$ (4.26)	$\psi_{GD}=\frac{\dot{E}_{xP,GD}}{\dot{E}_{xF,GD}}$ (4.27)

Table 4.8. Equations of exergy balance and efficiency of the COGEN and its components (continued)

Components (Control Volume)	**Exergy Relations**	**Exergy efficiency equation**
	$\dot{E}_{x,F,GD} = \begin{bmatrix} (\dot{E}x_{2.1}+\dot{E}x_{1})+ \\ (\dot{E}x_{5.1}+\dot{E}x_{5.2}+\dot{E}x_{6.1}+\dot{E}x_{6.2})+ \\ \begin{pmatrix} \dot{E}x_{9.1}+\dot{E}x_{9.2}+\dot{E}x_{10.1}+ \\ \dot{E}x_{10.2}+\dot{E}x_{10.3} \end{pmatrix} \end{bmatrix}$ (4.28) $\dot{E}_{x,P,GD} = \begin{bmatrix} (\dot{W}_{14})+(\dot{E}x_{7.1}+\dot{E}x_{7.2}) \\ +(\dot{E}x_{11.1}+\dot{E}x_{11.2}) \end{bmatrix}$ (4.29) Exhaust (unused) gases loses of COGEN: $\begin{pmatrix} \dot{E}x_{8.1}+\dot{E}x_{8.2}+\dot{E}x_{8.3} \\ \dot{E}x_{12.1}+\dot{E}x_{12.2}+\dot{E}x_{12.3} \end{pmatrix}$ (4.30) $\dot{E}_{x,D,COGEN} = \dot{E}_{x,F,WD} - \dot{E}_{x,P,WD} - \dot{E}_{x,L,WD}$ (4.31)	$\psi_{GD}= \frac{\dot{E}_{xP,COGEN}}{\dot{E}_{xF,COGEN}}$ (4.32)

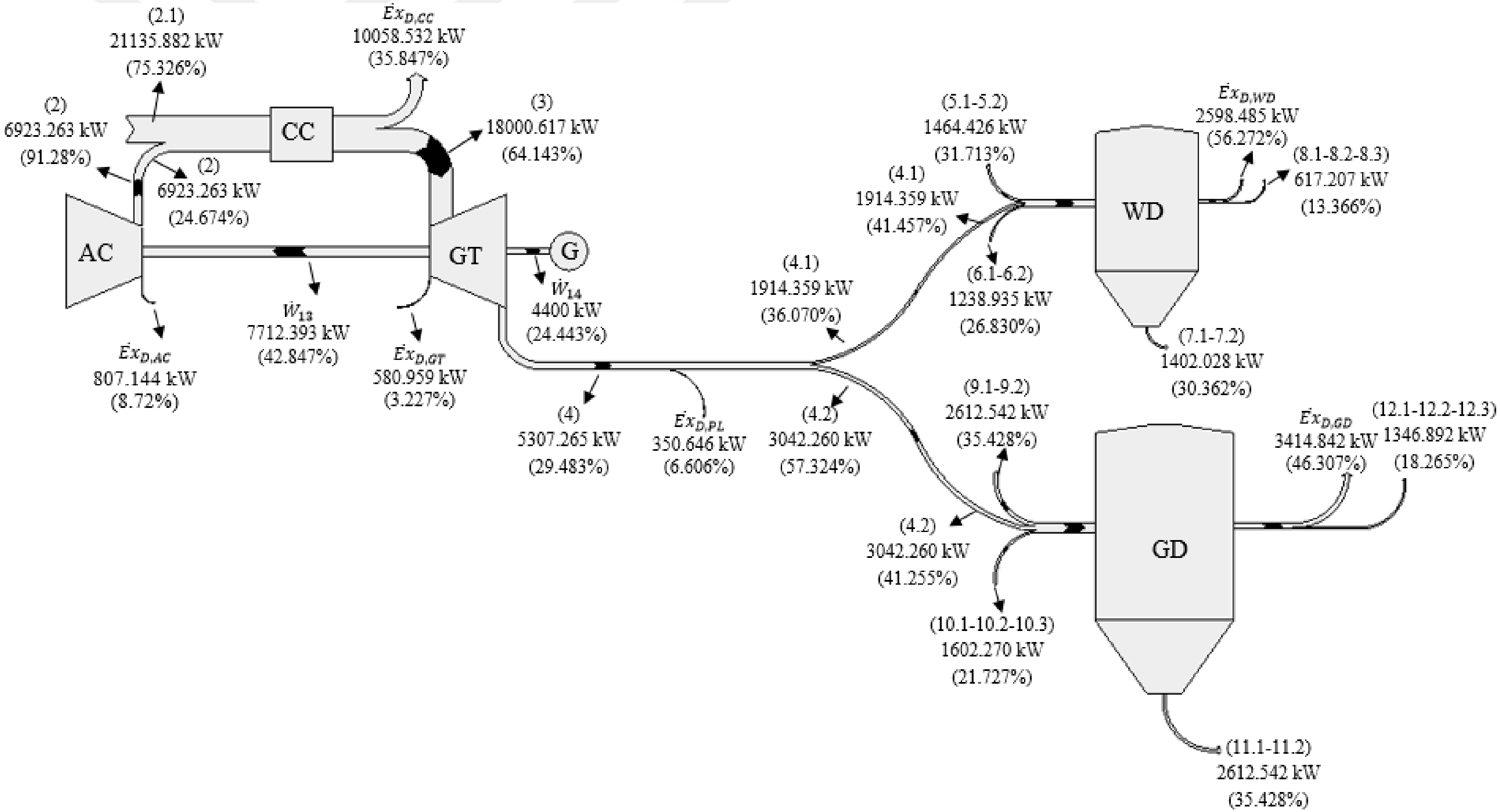


Figure 4.5. Exergy flow (Grassmann) diagram of the COGEN at a dead state temperature of 30 °C

4.3. Conventional Exergoeconomic Balance Equations of COGEN and Its Components

In order to perform exergoeconomic analysis of the system, plant economic life time "n", total annual operating hours of the system operation at full load "τ", interest rate "i", maintenance factor "Ω" (if not known), energy costs used in the system (electrical, natural gas etc.) and salvage value "μ" must be known. In addition, economic constants obtained using these assumptions can be determined such as the present value factor "PWF", the recovery factor of initial capital cost "CRF", the present monetary value "$\dot{P}\dot{W}$" and the annual capital cost "$\dot{C}\dot{A}_{system}$". The values of these assumptions and economic constants mentioned above are given in Table 4.9 for COGEN.

Table 4.9. Assumptions and economic constants of COGEN and its components

Parameter	**Unit**	**Value**
Plant economic life "n"	year	25
Total annual operating hours of the system operation at full load "τ"	hour	7590
Interest rate "i"[1]	%	10
Cost per exergy unit of natural gas[2]	\$/GJ	6.970
Maintenance factor "Ω" (calculated for each component separately.)	-	-
Salvage value "μ"	%	15
Present worth factor "PWF"	-	0.0736
Capital recovery factor "CRF"	-	0.11874

The purchased equipment cost "PEC", the total capital cost "$\dot{Z}_k$" the investment cost "$\dot{Z}_k^{CI}$", the operation and maintenance cost "$\dot{Z}_k^{OM}$" of kth components are presented Table 4.10. In the first column, besides the purchase costs of the system components, other costs, which consist of project management, engineering, machinery, equipment and labor costs are shown. The maintenance factor value "Ω" is not used in calculations because the cost of operation and maintenance value of each component is in different rates.

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[1] Central Bank of the Republic of Turkey Head Office annual interest rate for 2020.

[2] The natural gas unit price stated in the Uşak Industry Estate Zone in Turkey 2019-November natural gas bill has been accepted. (1 \$= 5.95 TL [58]) Natural gas= 0.14931 TL/kWh or 6.97 \$/GJ.

Table 4.10. The purchased equipment cost, hourly levelized cost rates associated with capital investments and the operation and maintenance cost of COGEN and its components

Equipment	**PEC (x10^3\$)**	**$\dot{Z}_k^{CI}$ (\$/h)**	**$\dot{Z}_k^{OM}$ (\$/h)**	**$\dot{Z}_k$ (\$/h)**
Air compressor (AC)	924.3	16.392	14.932	31.324
Combustion chamber (CC)	52.5	0.931	0.848	1.780
Gas Turbine (GT)	762.3	13.520	12.315	25.835
Wall tile dryer (WD)	139	2.465	1.848	4.313
Ground tile dryer (WD)	198	3.512	2.632	6.143
Piping line (PL)	135	2.394	1.318	3.712
Other costs	180			
Total	2391.1	39.214	33.893	73.107

The cost balance and auxiliary equations for each component in COGEN, as well as exergoeconomic factor "f_k" and relative cost difference "r_k", can be seen in Table 4.11.

Table 4.11. Exergoeconomic cost balance equations, exergoeconomic factor and relative cost difference for components of COGEN

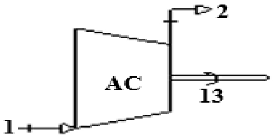
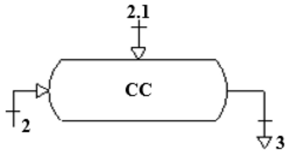
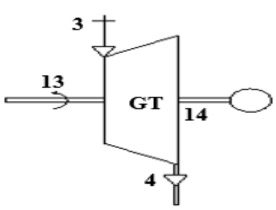
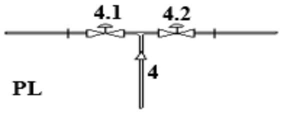
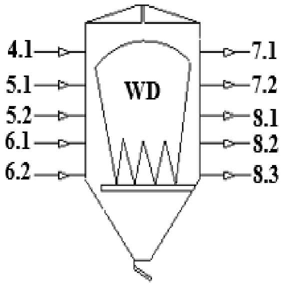
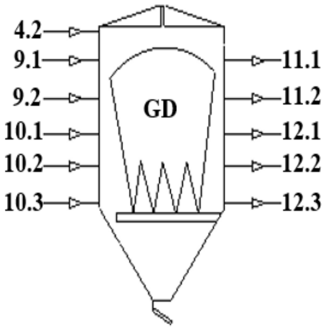
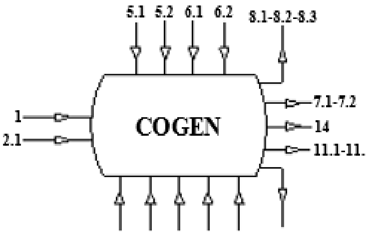
Components (Control Volume)	**Main equations (Cost balance) and auxiliary**	**"f_k" and "r_k" "r_k"**
	$\dot{C}_{F,AC=}c_W\dot{W}_{13}$ (4.33) $\dot{C}_{P,AC=}\dot{C}_2-\dot{C}_1$ (4.34) $\dot{C}_{P,AC}=\dot{C}_{F,AC}+\dot{Z}_{AC}$ (4.35) $\dot{C}_1=0$ (Accepted)	$f_{AC}=\frac{\dot{Z}_{AC}}{\dot{Z}_{AC}+c_W\dot{E}x_{D,AC}}$ (4.36) $r_{AC}=\frac{c_{F,AC}-c_{P,AC}}{c_{F,AC}}$ (4.37)
	$\dot{C}_{F,CC=}\dot{C}_{2.1}$ (4.38) $\dot{C}_{P,CC=}\dot{C}_3-\dot{C}_2$ (4.39) $\dot{C}_{P,AC}=\dot{C}_{F,CC}+\dot{Z}_{CC}$ (4.40)	$f_{CC}=\frac{\dot{Z}_{CC}}{\dot{Z}_{CC}+c_{2.1}\dot{E}x_{D,CC}}$ (4.41) $r_{CC}=\frac{c_{F,CC}-c_{P,CC}}{c_{F,CC}}$ (4.42)
	$\dot{C}_{F,GT=}\dot{C}_3-\dot{C}_4$ (4.43) $\dot{C}_{P,GT=}c_W(\dot{W}_{13}+\dot{W}_{14})$(4.44) $\dot{C}_{P,GT}=\dot{C}_{F,GT}+\dot{Z}_{GT}$ (4.45) $\frac{\dot{C}_4}{\dot{E}x_4}=\frac{\dot{C}_3}{\dot{E}x_3}$ F-rule (4.46) $\frac{\dot{C}_{14}}{\dot{W}_{14}}=\frac{\dot{C}_{13}}{\dot{W}_{13}}$P-rule (4.47)	$f_{GT}=\frac{\dot{Z}_{GT}}{\dot{Z}_{GT}+c_{F,GT}\dot{E}x_{D,GT}}$ (4.48) $r_{GT}=\frac{c_{F,GT}-c_{P,GT}}{c_{F,GT}}$ (4.49)

Table 4.11. Exergoeconomic cost balance equations, exergoeconomic factor and relative cost difference for components of COGEN (continued)

Components **(Control Volume)**	**Main equations (Cost balance) and** **auxiliary equations**	**"f_k" and "r_k"**
	$\dot{C}_{F,PL}=\dot{C}_4$ (4.50) $\dot{C}_{P,PL}=\dot{C}_{4.1}+\dot{C}_{4.2}$ (4.51) $\dot{C}_{P,PL}=\dot{C}_{F,PL}+\dot{Z}_{PL}$ (4.52) $\frac{\dot{C}_4}{\dot{E}x_4}=\frac{\dot{C}_{4.1}}{\dot{E}x_{4.1}}=\frac{\dot{C}_{4.2}}{\dot{E}x_{4.2}}$ F − rule (4.53)	$f_{PL}=\frac{\dot{Z}_{PL}}{\dot{Z}_{PL}+c_4\dot{E}x_{D,PL}}$ (4.54) $r_{GT}=\frac{c_{F,PL}-c_{P,PL}}{c_{F,PL}}$ (4.55)
	$\dot{C}_{F,WD}=\begin{bmatrix}(\dot{C}_{4.1}+\dot{C}_{6.1}+\dot{C}_{6.2})\\-(\dot{C}_{8.2}+\dot{C}_{8.3})\end{bmatrix}$ (4.56) $\dot{C}_{P,WD}=\begin{bmatrix}(\dot{C}_{7.1}+\dot{C}_{7.2}+\dot{C}_{8.1})\\-(\dot{C}_{5.1}+\dot{C}_{5.2})\end{bmatrix}$ (4.57) $\dot{C}_{P,WD}=\dot{C}_{F,WD}+\dot{Z}_{WD}$ (4.58) $c_{8.1}=c_{8.2}=c_{8.3}$ (Assumption) $\dot{C}_{6.2}=0$ (Accepted)	$f_{WD}=$ $\frac{\dot{Z}_{WD}}{\dot{Z}_{WD}+c_{F,WD}\dot{E}x_{D,WD}}$ (4.59) $r_{GD}=\frac{c_{F,WD}-c_{P,WD}}{c_{F,WD}}$ (4.60)
	$\dot{C}_{F,GD}=$ $\begin{bmatrix}(\dot{C}_{4.2}+\dot{C}_{10.1}+\dot{C}_{10.2}+\dot{C}_{10.3})\\-(\dot{C}_{12.2}+\dot{C}_{12.3})\end{bmatrix}$ (4.61) $\dot{C}_{P,GD}=\begin{bmatrix}(\dot{C}_{11.1}+\dot{C}_{11.2}+\dot{C}_{12.1})\\-(\dot{C}_{9.1}+\dot{C}_{9.2})\end{bmatrix}$ (4.62) $\dot{C}_{P,GD}=\dot{C}_{F,GD}+\dot{Z}_{GD}$ (4.63) $c_{12.1}=c_{12.2}=c_{12.3}$ (Assumption) $\dot{C}_{10.2}=\dot{C}_{10.3}=0$ (Accepted)	$f_{GD}=$ $\frac{\dot{Z}_{GD}}{\dot{Z}_{GD}+c_{F,GD}\dot{E}x_{D,GD}}$ (4.64) $r_{GD}=\frac{c_{F,GD}-c_{P,GD}}{c_{F,GD}}$ (4.65)
	$\dot{C}_{F,COGEN}=$ $\begin{bmatrix}(\dot{C}_1+\dot{C}_{2.1})+\\(\dot{C}_{5.1}+\dot{C}_{5.2}+\dot{C}_{6.1}+\dot{C}_{6.2})+\\(\dot{C}_{9.1}+\dot{C}_{9.2}+\dot{C}_{10.1}+\dot{C}_{10.2}+\dot{C}_{10.3})\end{bmatrix}$ (4.66) $\dot{C}_{P,COGEN}=\begin{bmatrix}(\dot{C}_{14})+(\dot{C}_{7.1}+\dot{C}_{7.2})\\+(\dot{C}_{11.1}+\dot{C}_{11.2})\end{bmatrix}$ (4.67) $\dot{C}_{L,COGEN}=\begin{bmatrix}(\dot{C}_{8.1}+\dot{C}_{8.2}+\dot{C}_{8.3})\\+(\dot{C}_{11.1}+\dot{C}_{11.2}+\dot{C}_{11.3})\end{bmatrix}$ (4.68) $\dot{C}_{P,COGEN}=$ $\dot{C}_{F,COGEN}+\dot{C}_{L,COGEN}+\dot{Z}_{tot}$ (4.69)	$f_{COGEN}=\frac{\dot{Z}_{tot}}{\dot{Z}_{tot}+\dot{C}_D+\dot{C}_L}$ (4.70) $r_{CONGEN}=$ $\frac{c_{F,COGEN}-c_{P,COGEN}}{c_{F,COGEN}}$ (4.71)

The cost per exergy values of the combustion gases obtained from the waste heat recovery system, water of slurry, humidity of masse are considered to be zero. The following equations are used to calculate the cost per exergy values of net turbine work and compressor work at 10°C.

$$\frac{\dot{C}_{14}}{\dot{W}_{14}} = \frac{\dot{C}_{13}}{\dot{W}_{13}} = \frac{\dot{C}_{14}}{15.840} = \frac{\dot{C}_{13}}{27.765} = c_W \tag{4.72}$$

For air compressor:

$$\dot{C}_{P,AC} = \dot{C}_{F,AC} + \dot{Z}_{AC} \tag{4.73}$$

$$\dot{C}_2 - \dot{C}_1 = c_W\dot{W}_{13} + \dot{Z}_{AC} \rightarrow \dot{C}_2 - 0 = c_W 27.765 + 31.324 \text{ and } \dot{C}_1 = 0 \text{ (accepted)} \tag{4.74}$$

For combustion chamber;

$$\dot{C}_{P,CC} = \dot{C}_{F,CC} + \dot{Z}_{CC} \rightarrow \dot{C}_3 - \dot{C}_2 = c_{2.1}\dot{Ex}_{2.1} + 1.780 \tag{4.75}$$

if "$\dot{C}_2$" is substituted in the equation below;

$$\dot{C}_3 - (c_W 27.765 + 31.324) = c_{2.1}76.051 + 1.780 \tag{4.76}$$

The natural gas "$c_{2.1}$" is determined 6.97 $/GJ in Ref.

$$\dot{C}_3 = c_W 27.765 + 563.179 \tag{4.77}$$

For gas turbine;

$$\frac{\dot{C}_4}{20.766} = \frac{\dot{C}_3}{66.286} \rightarrow \frac{\dot{C}_4}{20.766} = \frac{c_W 27.765 + 563.179}{66.286} \tag{4.78}$$

$$\dot{C}_4 = c_W 8.698 + 176.432 \tag{4.79}$$

$$\dot{C}_{P,GT} = \dot{C}_{F,GT} + \dot{Z}_{GT} \tag{4.80}$$

$$\dot{C}_{F,GT=}\dot{C}_3 - \dot{C}_4 \tag{4.81}$$

$$c_W\left(\dot{W}_{13} + \dot{W}_{14}\right) = \left(\dot{C}_3 - \dot{C}_4\right) + 25.835 \tag{4.82}$$

$$c_W 43.605 = c_W 19.067 + 386.747 + 25.84 \rightarrow 24.538 c_W = 412.587 \tag{4.83}$$

"c_W" 16.813 $/GJ is found from the result of the above equation at 10°C.

The above equations are applied for the other dead state temperatures and the cost per exergy values of net turbine work and compressor are determined as to be 17.009 $/GJ, 17.215 $/GJ, 17.414 $/GJ, 17.612 $/GJ for 15 °C, 20 °C, 25 °C and 30 °C, respectively. The cost per unit of exergy and cost of the exergy stream of entering and leaving materials are listed Table 4.12 for the five different dead state (environment) temperatures varying from 10°C to 30°C (interval of 5°C).

Table 4.12. Cost per unit of exergy and the exergy cost rate of stream points in COGEN

Stream No	*T*=10°C			*T*=15°C			*T*=20°C			*T*=25°C			*T*=30°C		
	$\dot{Ex}$ (GJ/h)	c ($/GJ)	$\dot{C}$ ($/h)	$\dot{Ex}$ (GJ/h)	c ($/GJ)	$\dot{C}$ ($/h)	$\dot{Ex}$ (GJ/h)	c ($/GJ)	$\dot{C}$ ($/h)	$\dot{Ex}$ (GJ/h)	c ($/GJ)	$\dot{C}$ ($/h)	$\dot{Ex}$ (GJ/h)	c ($/GJ)	$\dot{C}$ ($/h)
1	0.270	0.000	0.000	0.214	0.000	0.000	0.148	0.000	0.000	0.104	0.000	0.000	0.065	0.000	0.000
2	25.305	19.685	498.137	25.207	19.978	503.579	25.092	20.297	509.298	25.005	20.589	514.824	24.924	20.876	520.321
2.1	76.051	6.970	530.075	76.060	6.970	530.138	76.070	6.970	530.208	76.079	6.970	530.271	76.089	6.970	530.340
3	66.286	15.539	1029.99	65.912	15.710	1035.49	65.517	15.893	1041.28	65.156	16.067	1046.875	64.802	16.241	1052.441
4	20.766	15.539	322.683	20.347	15.710	319.651	19.911	15.893	316.446	19.505	16.067	313.387	19.106	16.241	310.301
4.1	7.516	16.773	126.066	7.359	16.972	124.897	7.194	17.188	123.650	7.042	17.391	122.467	6.892	17.598	121.285
5.1	5.025	13.228	66.471	5.022	13.263	66.607	5.019	13.295	66.728	5.016	13.324	66.833	5.015	13.351	66.955
5.2	0.289	3.153	0.911	0.279	3.219	0.898	0.270	3.279	0.885	0.263	3.338	0.878	0.257	3.391	0.871
6.1	4.303	6.970	29.992	4.304	6.970	29.999	4.304	6.970	29.999	4.305	6.970	30.006	4.306	6.970	30.013
6.2	0.193	0.000	0.000	0.183	0.000	0.000	0.173	0.000	0.000	0.163	0.000	0.000	0.154	0.000	0.000
7.1	5.031	13.628	68.562	5.027	13.671	68.724	5.023	13.711	68.870	5.020	13.747	69.010	5.017	13.781	69.139
7.2	0.035	4.209	0.147	0.033	4.297	0.142	0.032	4.378	0.140	0.031	4.456	0.138	0.030	4.527	0.136
8.1	2.823	51.387	145.066	2.667	54.923	146.480	2.516	58.992	148.424	2.355	63.825	150.308	2.199	69.380	152.567
8.2	0.048	51.387	2.467	0.040	54.923	2.197	0.032	58.992	1.888	0.025	63.825	1.596	0.019	69.380	1.318
8.3	0.224	51.387	11.511	0.167	54.923	9.172	0.106	58.992	6.253	0.054	63.825	3.447	0.004	69.380	0.278
4.2	11.944	16.773	200.337	11.694	16.972	198.471	11.433	17.188	196.510	11.191	17.391	194.623	10.952	17.598	192.733
9.1	9.366	13.065	122.367	9.359	13.098	122.584	9.353	13.128	122.786	9.348	13.156	122.982	9.344	13.180	123.154
9.2	0.548	2.723	1.492	0.526	2.783	1.464	0.509	2.839	1.445	0.494	2.892	1.429	0.483	2.941	1.421
10.1	4.939	6.970	34.425	4.940	6.970	34.432	4.940	6.970	34.432	4.941	6.970	34.439	4.941	6.970	34.439
10.2	0.212	0.000	0.000	0.200	0.000	0.000	0.188	0.000	0.000	0.176	0.000	0.000	0.165	0.000	0.000
10.3	0.827	0.000	0.000	0.785	0.000	0.000	0.739	0.000	0.000	0.700	0.000	0.000	0.661	0.000	0.000
11.1	9.375	13.374	125.381	9.367	13.414	125.649	9.360	13.450	125.892	9.354	13.484	126.129	9.349	13.514	126.342
11.2	0.065	3.540	0.230	0.063	3.618	0.228	0.060	3.691	0.221	0.058	3.760	0.218	0.056	3.823	0.214
12.1	5.283	36.861	194.737	4.992	39.061	194.993	4.702	41.636	195.772	4.412	44.466	196.184	4.121	47.717	196.642
12.2	0.087	36.861	3.207	0.078	39.061	3.047	0.069	41.636	2.873	0.061	44.466	2.712	0.054	47.717	2.577
12.3	1.118	36.861	41.211	1.003	39.061	39.178	0.878	41.636	36.556	0.773	44.466	34.372	0.673	47.717	32.114
13	27.765	16.813	466.813	27.765	17.009	472.255	27.765	17.215	477.974	27.765	17.414	483.500	27.765	17.612	488.997
14	15.840	16.813	266.318	15.840	17.009	269.423	15.840	17.215	272.686	15.840	17.414	275.838	15.840	17.612	278.974

4.4. Environmental Balance Equations of COGEN and Its Components

The LCA is used to determine the environmental impacts of products, processes or services in their production, use and disposal processes throughout lifetime. The LCA, which is applied within the scope of (ISO14004), uses ECO-indicator99 values to determine the environmental effects of each component "$\dot{Y}_k$" and the entering materials for components. In exergoenvironmental analysis, the environmental impact rate "$\dot{B}_j$" (mpts/h) is found for each stream point by combining exergy streams "$\dot{E}x_j$" and the specific environmental impact rate "b_j" (mpts/GJ) in the system. Firstly, the total environmental effects of gases such as CO_2 (5.454 mPts/kg) emitted as a result of chemical reactions, associated with pollutant formation for CC, WD and GD are given in Table 4.13 [59]. The information of the materials that make up each component and their environmental impacts of these components in terms of construction organization "$\dot{Y}_k^{CO}$", operation and maintenance "$\dot{Y}_k^{OM}$" (accepted as 20% of "$\dot{Y}_k^{CO}$"), disposal "$\dot{Y}_k^{DI}$" throughout their lifetime, are given in Table 4.14 [60]. In this study, the disposal effects of the components are ignored, since it is assumed that the gas turbine and spray dryers can be reused after revision maintenance [61]. The lifetime "n" of the COGEN, which is also stated in the exergoeconomic analysis, is assumed to be 25 years, while the annual working hour "τ" is considered to be 7950 hours. The environmental impact rate of the process water and natural gas are accepted as 0.026 mPts/kg and 143.9 mPts/kg, respectively [37]. The environmental impact rate equations of fuels and products with exergoenvironmental balances and auxiliary equations for the components of the COGEN are given Table 4.15 [37]. The specific environmental impact rate "b_j" and environmental impact rate "$\dot{B}_j$" of the exergy stream of entering and leaving materials to components are listed Table 4.16 for the five different dead state (environment) temperatures varying from 10°C to 30°C (interval of 5°C).

Table 4.13. Environmental impact of pollutant formation for CC, WD and GD

Components	$b_{CO_2}^{PF}$ **(mPts/kg)**	$\dot{m}_{i,out}$ **(kg/h)**	$\dot{m}_{i,in}$ **(kg/h)**	$\dot{B}_k^{PF}$ **(mPts/h)**	$\dot{B}_{tot}^{PF}$ **(mPts/h)**
CC	5.454	51.254	4125.600	22221.482	24925.685
WD		2.760	233.750	1259.819	
GD		3.170	268.000	1444.383	

Table 4.14. Material composition rate and ECO-indicator values of components

Components	**Material**	**Eco-ind of materials (mPts/kg)**	**Material (%)**	**Weight (kg)**	**Material (mPts/kg)**	**Process (mPts/kg)**	**Disposal (mPts/kg)**	**Total (mPts/kg)**	**Total (mPts)**	**$\dot{Y}_k$ (mPts/h)**
AC	Steel	86	33%	6040	130.68	26.136	0	156.816	947168.64	4.992
	Steel low alloy	110	45%							
	Cast iron	240	22%							
CC	Steel	86	33%	3844	638.08	127.616	0	765.696	2943335.4	15.512
	Steel high alloy	910	67%							
GT	Steel	86	25%	6445	704	140.8	0	844.8	5444736	28.694
	Steel high alloy	910	75%							
PL	Steel low alloy	110	100%	11100	110	22	0	132	1465200	7.722
WD	Steel	86	10%	54000	320.6	64.12	0	384.72	20774880	109.486
	Steel low alloy	110	55%							
	Steel high alloy	910	25%							
	Cast iron	240	10%							
GD	Steel	86	10%	73000	320.6	64.12	0	384.72	28084560	148.008
	Steel low alloy	110	55%							
	Steel high alloy	910	25%							
	Cast iron	240	10%							

Table 4.15. Environmental impact balance equations with auxiliary equations, “$f_{b,k}$” and “$r_{b,k}$” for components of COGEN

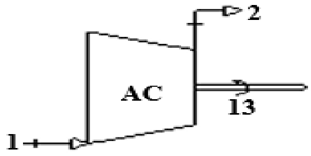
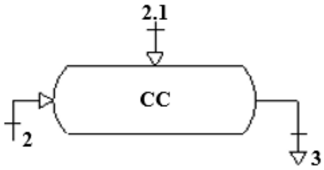
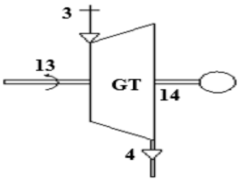
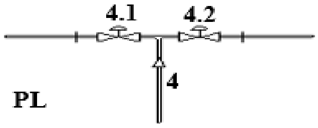
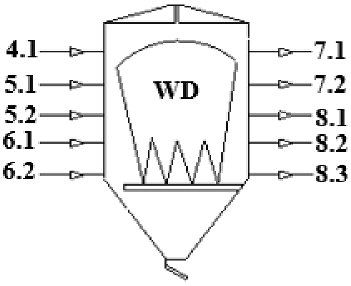
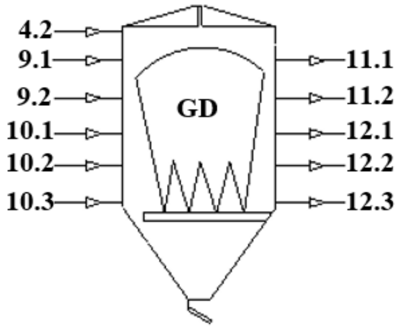
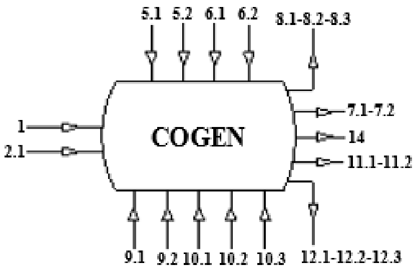
Components (Control Volume)	**Main equations (Environmental impact balance) and auxiliary equations**	**“$f_{b,k}$” and “$r_{b,k}$”**
	$\dot{B}_{F,AC=}b_W\dot{W}_{13}$ (4.84) $\dot{B}_{P,AC=}\dot{B}_2 - B_1$ (4.85) $\dot{B}_{P,AC} = \dot{B}_{F,AC} + \dot{Y}_{AC}$ (4.86) $\dot{B}_1 = 0$ (Accepted)	$f_{b,AC} = \frac{\dot{Y}_{AC}}{\dot{Y}_{AC}+b_W\dot{E}x_{D,AC}}$ (4.87) $r_{b,AC} = \frac{b_{F,AC}-b_{P,AC}}{b_{F,AC}}$ (4.88)
	$\dot{B}_{F,CC=}\dot{B}_{2.1}$ (4.89) $\dot{B}_{P,CC=}\dot{B}_3 - \dot{B}_2$ (4.90) $\dot{B}_{P,AC} = \dot{B}_{F,CC} + \dot{Y}_{CC} + \dot{B}_{CC}^{PF}$ (4.91)	$f_{b,CC} =$ $\frac{\dot{Y}_{CC}+\dot{B}_{CC}^{PF}}{\dot{Y}_{CC}+\dot{B}_{CC}^{PF}+b_{2.1}\dot{E}x_{D,CC}}$ (4.92) $r_{b,CC} = \frac{b_{F,CC}-b_{P,CC}}{b_{F,CC}}$ (4.93)
	$\dot{B}_{F,GT=}\dot{B}_3 - \dot{B}_4$ (4.94) $\dot{B}_{P,GT=}b_W\left(\dot{W}_{13} + \dot{W}_{14}\right)$ (4.95) $\dot{B}_{P,GT} = B_{F,GT} + \dot{Y}_{GT}$ (4.96) $\frac{\dot{B}_4}{\dot{E}x_4} = \frac{\dot{B}_3}{\dot{E}x_3}$ F-rule (4.97) $\frac{\dot{B}_{14}}{\dot{W}_{14}} = \frac{\dot{B}_{13}}{\dot{W}_{13}}$ P-rule (4.98)	$f_{b,GT} = \frac{\dot{Y}_{GT}}{\dot{Y}_{GT}+b_{F,GT}\dot{E}x_{D,GT}}$ (4.99) $r_{b,GT} = \frac{b_{F,GT}-b_{P,GT}}{b_{F,GT}}$ (4.100)
	$\dot{B}_{F,PL=}\dot{B}_4$ (4.101) $\dot{B}_{P,PL=}\dot{B}_{4.1} + \dot{B}_{4.2}$ (4.102) $\dot{B}_{P,PL} = \dot{B}_{F,PL} + \dot{Y}_{PL}$ (4.103) $\frac{\dot{B}_4}{\dot{E}x_4} = \frac{\dot{B}_{4.1}}{\dot{E}x_{4.1}} = \frac{\dot{B}_{4.2}}{\dot{E}x_{4.2}}$ F − rule (4.104)	$f_{b,PL} = \frac{\dot{Y}_{PL}}{\dot{Y}_{PL}+b_4\dot{E}x_{D,PL}}$ (4.105) $r_{b,PL} = \frac{b_{F,PL}-b_{P,PL}}{b_{F,PL}}$ (4.106)
	$\dot{B}_{F,WD=}\begin{bmatrix}\left(\dot{B}_{4.1} + \dot{B}_{6.1} + \dot{B}_{6.2}\right)\\ -\left(\dot{B}_{8.2} + \dot{B}_{8.3}\right)\end{bmatrix}$ (4.107) $\dot{B}_{P,WD=}\begin{bmatrix}\left(\dot{B}_{7.1} + \dot{B}_{7.2} + \dot{B}_{8.1}\right)\\ -\left(\dot{B}_{5.1} + \dot{B}_{5.2}\right)\end{bmatrix}$ (4.108) $\dot{B}_{P,WD} = \dot{B}_{F,WD} + \dot{Y}_{WD} + \dot{B}_{WD}^{PF}$(4.109) $b_{8.1} = b_{8.2} = b_{8.3}$ (Assumption) $\dot{B}_{6.2} = 0$ (Accepted)	$f_{b,WD} =$ $\frac{\dot{Y}_{WD}+\dot{B}_{WD}^{PF}}{\dot{Y}_{WD}+\dot{B}_{WD}^{PF}+b_{F,WD}\dot{E}x_{D,WD}}$ (4.110) $r_{b,WD} = \frac{b_{F,WD}-b_{P,WD}}{b_{F,WD}}$ (4.111)

Table 4.15. Environmental impact balance equations with auxiliary equations, “$f_{b,k}$” and “$r_{b,k}$” for components of COGEN

Components (Control Volume)	**Main equations (Environmental impact balance) and auxiliary equations**	**Exergoenvironmental factor “f_k” and relative environmental impact difference “r_k”**
	$\dot{B}_{F,GD=}(\dot{B}_{4.2}+\dot{B}_{9.1}+\dot{B}_{9.2})$ (4.112) $+(\dot{B}_{10.1}+\dot{B}_{10.2}+\dot{B}_{10.3})$ (4.113) $\dot{B}_{P,GD=}(\dot{B}_{11.1}+\dot{B}_{11.2})$ (4.114) $\dot{B}_{P,GD}=\dot{B}_{F,GD}+\dot{Y}_{GD}+\dot{B}_{GD}^{PF}$ (4.115) $\frac{\dot{B}_{9.2}}{\dot{E}x_{9.2}}=\frac{\dot{B}_{11.2}}{\dot{E}x_{11.2}}=b_{water}$ (4.116) Assumptions: $\dot{B}_{7.1}=\dot{B}_{10.2}=\dot{B}_{10.3}=0$	$f_{b,GD}=$ $\frac{\dot{Y}_{GD}+\dot{B}_{GD}^{PF}}{\dot{Y}_{GD}+\dot{B}_{GD}^{PF}+b_{F,GD}\dot{E}x_{D,GD}}$ (4.117) $r_{b,GD}=\frac{b_{F,GD}-b_{P,GD}}{b_{F,GD}}$ (4.118)
	$\dot{B}_{F,COGEN=}$ $\begin{bmatrix}(\dot{B}_1+\dot{B}_{2.1})+\\(\dot{B}_{5.1}+\dot{B}_{5.2}+\dot{B}_{6.1}+\dot{B}_{6.2})+\\(\dot{B}_{9.1}+\dot{B}_{9.2}+\dot{B}_{10.1}+\dot{B}_{10.2}+\dot{B}_{10.3})\end{bmatrix}$ (4.119) $\dot{B}_{P,COGEN=}$ $\begin{bmatrix}(\dot{B}_{14})+(\dot{B}_{7.1}+\dot{B}_{7.2})+\\(\dot{B}_{11.1}+\dot{B}_{11.2})\end{bmatrix}$ (4.120) $\dot{B}_{L,COGEN=}$ $\begin{bmatrix}(\dot{B}_{8.1}+\dot{B}_{8.2}+\dot{B}_{8.3})+\\(\dot{B}_{11.1}+\dot{B}_{11.2}+\dot{B}_{11.3})\end{bmatrix}$ (4.121) $\dot{B}_{P,COGEN}=$ $\dot{B}_{F,COGEN}+\dot{B}_{L,COGEN}+\dot{Y}_{tot}+\dot{B}_{tot}^{PF}$ (4.122)	$f_{b,COGEN}=$ $\frac{\dot{Y}_{tot}+\dot{B}_{tot}^{PF}}{\dot{Y}_{tot}+\dot{B}_{tot}^{PF}+(\dot{B}_D+\dot{B}_L)_{COGEN}}$ (4.123) $r_{b,COGEN}=$ $\frac{b_{F,COGEN}-b_{P,COGEN}}{b_{F,COGEN}}$ (4.124)

The following equations are used to calculate the environmental impact rate per exergy values of net turbine work and compressor work at 10°C;

$$\frac{\dot{B}_{14}}{\dot{W}_{14}}=\frac{\dot{B}_{13}}{\dot{W}_{13}}=\frac{\dot{B}_{14}}{15.84}=\frac{\dot{B}_{13}}{27.765}=b_W \tag{4.125}$$

For air compressor:

$$\dot{B}_{P,AC}=\dot{B}_{F,AC}+\dot{Y}_{AC} \tag{4.126}$$

$$\dot{B}_2-\dot{B}_1=b_W\dot{W}_{13}+\dot{Y}_{AC}\rightarrow\dot{B}_2-0=b_W27.765+4.992 \text{ and } \dot{B}_1=0 \text{ (accepted)} \tag{4.127}$$

For combustion chamber;

$$\dot{B}_{P,AC} = \dot{B}_{F,CC} + \dot{Y}_{CC} + \dot{B}_{CC}^{PF} \rightarrow \dot{B}_3 - \dot{B}_2 = b_{2.1}\dot{E}x_{2.1} + 15.512 + 22221.482 \quad (4.128)$$

if "$\dot{B}_2$" is substituted in the equation below;

$$\dot{B}_3 - (b_W 27.765 + 4.992) = b_{2.1}76.051 + 22236.994 \quad (4.129)$$

The natural gas "$b_{2.1}$" is determined 2942.663 mPts/GJ in Ref. (4.130)

$$\dot{B}_3 = b_W 27.765 + 246024.466 \quad (4.131)$$

For gas turbine;

$$\frac{\dot{B}_4}{20.766} = \frac{\dot{B}_3}{66.286} \rightarrow \frac{\dot{B}_4}{20.766} = \frac{b_W 27.765 + 246024.466}{66.286} \quad (4.132)$$

$$\dot{B}_4 = b_W 8.698 + 77074.255 \quad (4.133)$$

$$\dot{B}_{P,GT} = \dot{B}_{F,GT} + \dot{Y}_{GT} \quad (4.134)$$

$$\dot{B}_{F,GT=}\dot{B}_3 - \dot{B}_4 \quad (4.135)$$

$$b_W\left(\dot{W}_{13} + \dot{W}_{14}\right) = \left(\dot{B}_3 - \dot{B}_4\right) + 28.694 \quad (4.136)$$

$$b_W 43.605 = b_W 19.067 + 168950.211 + 28.694 \rightarrow 24.538 b_W = 168978.905 \quad (4.137)$$

"b_W" 6886.644 is found from the result of the above equation at 10°C.

The equations used for 10°C dead states temperature are applied for 15°C, 20°C, 25°C, 30°C and environmental impact rates per exergy (mPts/GJ) of turbine and compressor work "b_W" are calculated as 6968.664 mPts/GJ, 7055.500 mPts/GJ, 7138.658 mPts/GJ, 7222.275 mPts/GJ, respectively.

Table 4.16. Environmental impact per unit of exergy and the environmental impact rate of stream points in COGEN

Stream No	*T*=10°C			*T*=15°C			*T*=20°C			*T*=25°C			*T*=30°C		
	$\dot{Ex}$ (GJ/h)	b (mPts/GJ)	$\dot{B}$ (mPts/h)	$\dot{Ex}$ (GJ/h)	b (mPts/GJ)	$\dot{B}$ (mPts/h)	$\dot{Ex}$ (GJ/h)	b (mPts/GJ)	$\dot{B}$ (mPts/h)	$\dot{Ex}$ (GJ/h)	b (mPts/GJ)	$\dot{B}$ (mPts/h)	$\dot{Ex}$ (GJ/h)	b (mPts/GJ)	$\dot{B}$ (mPts/h)
1	0.270	0.00	0.00	0.214	0.00	0.00	0.148	0.00	0.00	0.104	0.00	0.00	0.065	0.00	0.00
2	25.305	7556.31	191212.55	25.207	7676.04	193489.83	25.092	7807.31	195900.95	25.005	7926.81	198209.88	24.924	8045.72	200531.59
2.1	76.051	2942.66	223792.24	76.060	2942.31	223792.10	76.070	2941.95	223794.14	76.079	2941.58	223792.46	76.089	2941.20	223792.97
3	66.286	6596.29	437241.78	65.912	6668.27	439518.92	65.517	6745.30	441932.08	65.156	6818.09	444239.33	64.802	6891.17	446561.55
4	20.766	6596.29	136978.56	20.347	6668.27	135679.29	19.911	6745.30	134305.67	19.505	6818.09	132986.85	19.106	6891.17	131662.69
4.1	7.516	7039.38	52907.98	7.359	7121.56	52407.56	7.194	7210.68	51873.63	7.042	7294.17	51365.55	6.892	7378.97	50855.86
5.1	5.025	11739.50	58990.99	5.022	11759.46	59056.01	5.019	11776.12	59104.35	5.016	11790.30	59140.14	5.015	11801.46	59184.32
5.2	0.289	10809.17	3123.85	0.279	10863.10	3030.80	0.270	10909.04	2945.44	0.263	10950.17	2879.89	0.257	10983.07	2822.65
6.1	4.303	2937.31	12639.24	4.304	2936.96	12640.68	4.304	2936.60	12639.13	4.305	2936.23	12640.47	4.306	2935.49	12640.22
6.2	0.193	0.00	0.00	0.183	0.00	0.00	0.173	0.00	0.00	0.163	0.00	0.00	0.154	0.00	0.00
7.1	5.031	13055.90	65684.23	5.027	13080.29	65754.62	5.023	13100.58	65804.21	5.020	13117.87	65851.71	5.017	13131.44	65880.43
7.2	0.035	14287.38	500.06	0.033	14353.00	473.65	0.032	14408.54	461.07	0.031	14457.89	448.19	0.030	14497.15	434.91
8.1	2.823	20306.00	57323.84	2.667	21668.78	57790.64	2.516	23235.33	58460.09	2.355	25100.84	59112.48	2.199	27253.38	59930.18
8.2	0.048	20306.00	974.69	0.040	21668.78	866.75	0.032	23235.33	743.53	0.025	25100.84	627.52	0.019	27253.38	517.81
8.3	0.224	20306.00	4548.54	0.167	21668.78	3618.69	0.106	23235.33	2462.94	0.054	25100.84	1355.45	0.004	27253.38	109.01
4.2	11.944	7039.38	84078.35	11.694	7121.56	83279.52	11.433	7210.68	82439.70	11.191	7294.17	81629.06	10.952	7378.97	80814.48
9.1	9.366	11249.74	105365.06	9.359	11268.09	105458.05	9.353	11283.39	105533.55	9.348	11296.37	105598.47	9.344	11306.58	105648.68
9.2	0.548	9515.12	5214.29	0.526	9564.81	5031.09	0.509	9607.15	4890.04	0.494	9645.12	4764.69	0.483	9675.49	4673.26
10.1	4.939	2936.84	14505.05	4.940	2936.49	14506.26	4.940	2936.12	14504.43	4.941	2935.75	14505.54	4.941	2935.37	14503.66
10.2	0.212	0.00	0.00	0.200	0.00	0.00	0.188	0.00	0.00	0.176	0.00	0.00	0.165	0.00	0.00
10.3	0.827	0.00	0.00	0.785	0.00	0.00	0.739	0.00	0.00	0.700	0.00	0.00	0.661	0.00	0.00
11.1	9.375	12281.68	115140.75	9.367	12303.51	115246.98	9.360	12321.66	115330.74	9.354	12337.06	115400.86	9.349	12349.14	115452.11
11.2	0.065	12241.72	795.71	0.063	12300.60	774.94	0.060	12350.46	741.03	0.058	12394.85	718.90	0.056	12430.15	696.09
12.1	5.283	14614.47	77208.25	4.992	15452.89	77140.83	4.702	16443.33	77316.54	4.412	17531.53	77349.11	4.121	18788.01	77425.39
12.2	0.087	14614.47	1271.46	0.078	15452.89	1205.33	0.069	16443.33	1134.59	0.061	17531.53	1069.42	0.054	18788.01	1014.55
12.3	1.118	14614.47	16338.98	1.003	15452.89	15499.25	0.878	16443.33	14437.24	0.773	17531.53	13551.87	0.673	18788.01	12644.33
13	27.765	6886.64	191207.56	27.765	6968.66	193484.84	27.765	7055.50	195895.96	27.765	7138.66	198204.89	27.765	7222.28	200526.60
14	15.840	6886.64	109084.38	15.840	6968.66	110383.57	15.840	7055.50	111759.12	15.840	7138.66	113076.37	15.840	7222.28	114400.92

4.5. The Real, Theoretical, Unavoidable Conditions of COGEN for Advanced Exergy, Advanced Exergoeconomic and Advanced Environmental Analysis

In advanced exergy analysis, unavoidable conditions must be determined in order to calculate the part of exergy destruction caused by technological restrictions. In addition, while the other components are considered to operate in theoretical conditions, the exergy destruction obtained by assuming that the studied component is operating in real conditions is known as the endogenous exergy destruction. Therefore, real, unavoidable and theoretical conditions of the system must be determined in order to perform advanced exergy analysis of a system. Hybrid cycles created to calculate the endogenous exergy destruction values of AC, CC and GT are shown in Figure 4.5, Figure 4.6 and Figure 4.7, respectively, while the cycle shown in Figure 4.8 is taken into account to calculate the avoidable and unavoidable exergy destruction of the these components [8].

- Process sequence for the hybrid cycle of AC: 1-2_{H_1}-$3_T(2_{H_1} + 2.1_T)$- 4_T

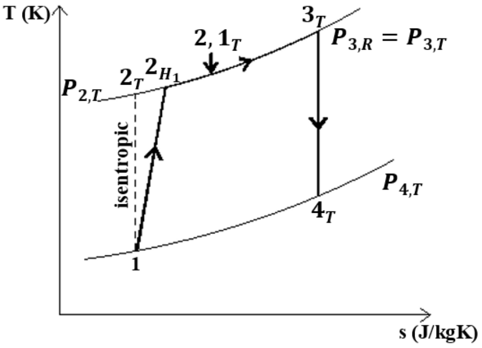


Figure 4.6. Hybrid cycle of AC

- Process sequence for the hybrid cycle of CC: 1-2_{H_2}-$3_T(2_{H_2} + 2.1_R)$- 4_T

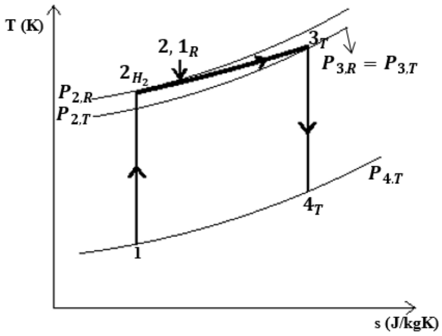


Figure 4.7. Hybrid cycle of CC

- Process sequence for the hybrid cycle of GT: 1-2_T-$3_T(2_T + 2.1_T)$- 4_R

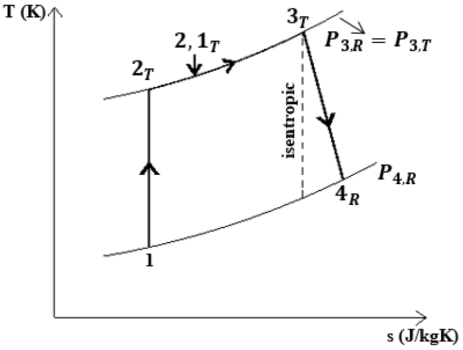


Figure 4.8. Hybrid cycle of GT

- Process sequence for the unavoidable cycle of gas turbine unit: 1-2_U-$3_U(2_U + 2.1_U)$- 4_U

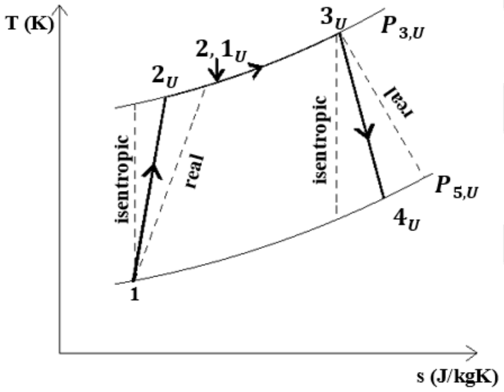


Figure 4.9. Unavoidable cycle of gas turbine unit

Assumptions of real, unavoidable and theoretical operation conditions for components of COGEN are shown Table 4.17.

Table 4.17. Assumptions of real, unavoidable and theoretical operation conditions for components of COGEN

Components	**State**	***T*** **(K)**	***P*** **(bar)**	**Real conditions (%)**	**Ideal conditions (%)**	**Unavoidable conditions (%)**	**Unavoidable investment cost (%)**
AC	2_T	574.09	10	η=82%	η=100%	η=95%	85%
	2_{H_1}	630.81	10				
	2_R	662	10.5				
	2_U	590.89	10.185				
CC	2_{H_2}	600	10.5	ΔP=%4.8	ΔP=%0	ΔP=%3	90%
	2.1_T	303.15	15				
	2.1_R	303.15	15				
	2.1_U	303.15	15				
GT	$4_R, 4_T$	1229.235	9.975	η=%87	η=%100	η=%97	80%
	4_U	1229.235	10.185				
	$5_R, 5_T$	783.15	1.05				
PL	-	-	-	ΔT=21°C η=97.3%	ΔT=0°C η=100%	ΔT=5.9°C η=99%	80%
WD	-	-	-	η=%34.55	η=100%	η=%97.33	70%
GD	-	-	-	η=%41.71	η=100%	η=%99.13	70%

5. RESULTS AND DISCUSSIONS

5.1. Evaluation of the System in terms of Conventional Exergy Analysis

In conventional exergy analysis, using the exergy flow rates of the materials (Table 4.7) and equation of exergy balance (Table 4.8), fuel exergy “$\dot{E}x_F$”, product exergy “$\dot{E}x_P$” and exergy destruction “$\dot{E}x_D$” values of each component are calculated for five different dead state temperatures. In addition, using the values obtained in this analysis, the exergetic evaluation parameters of the system are determined for five different dead state temperatures. All these values and parameters from conventional exergy analysis are listed in Table 5.1 for COGEN and its components.

According to fuel-product based exergy analysis, the following situations can be determined;

- When COGEN (the whole system) is examined, exergy destruction value “$\dot{E}x_D$” (kW), which is a measure of irreversibilities, is expected to be in the components where the combustion reactions occur the most. Therefore, as expected, highest exergy destruction value occur in CC (100058.532 kW at 30 °C). Maximum efficiency can be achieved by rearranging the amount of oxygen (fuel-air ratio) required for the combustion of a fuel containing carbon and hydrogen used in these components. On the other hand, the component with lowest exergy destruction value is determined as PL (350.646 kW at 30 °C) carrying hot air from the gas turbine unit to the spray dryers. The increase in exergy destruction values of other components except PL is directly proportional to the increase dead state temperatures while this relationship appear to have an inversely proportion for PL. For the COGEN, the increase in exergy destruction values is directly proportional to the increase in dead state temperatures, while the increase in exergy loss values “$\dot{E}x_L$” (kW) is inversely proportional to the increase in dead state temperatures. The effects of dead state temperatures on exergy destruction values of components and COGEN are illustrated in Figure 5.1 and Figure 5.2.

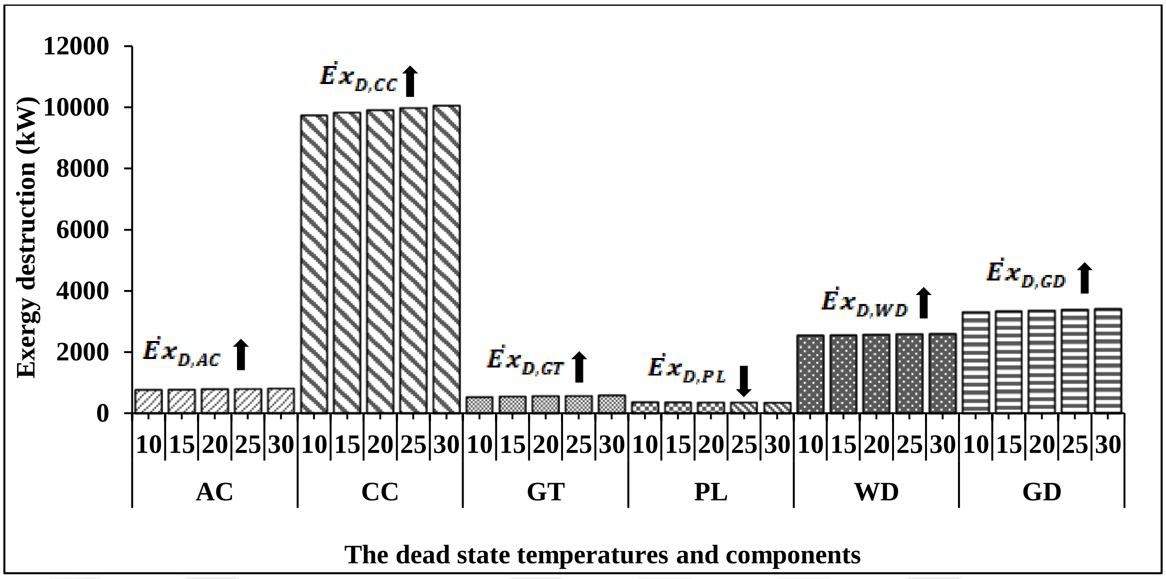


Figure 5.1. Effect of dead state temperatures on the exergy destruction of components

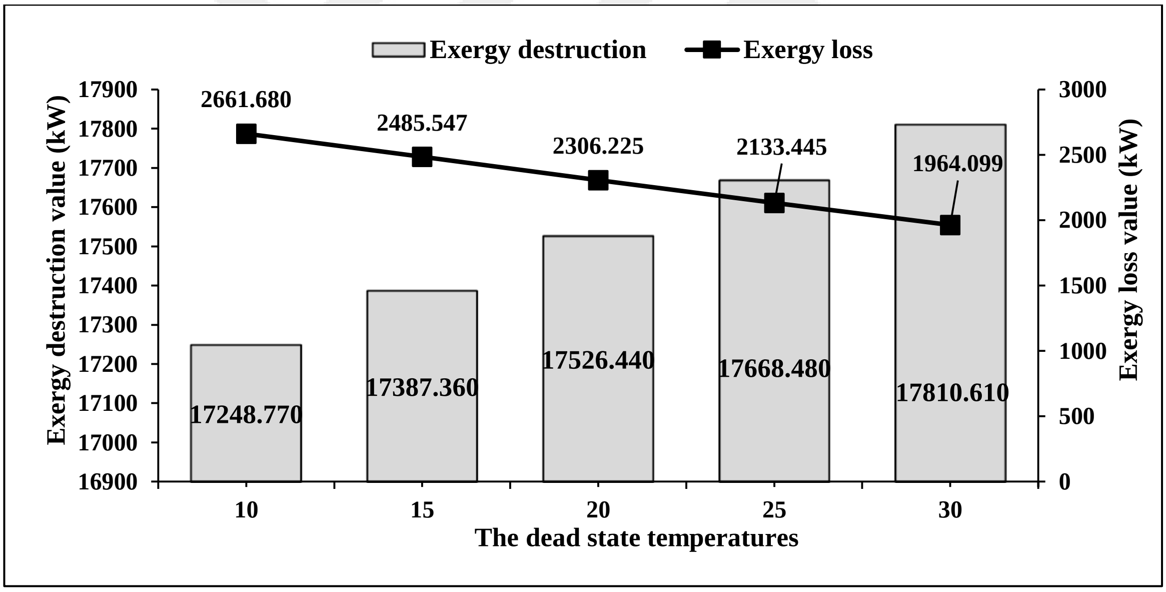


Figure 5.2. Effect of dead state temperatures on the exergy destruction and exergy loss of COGEN

- Among the components, the highest exergy efficiency rate is observed in GT (95.791% at 10°C), while the lowest exergy efficiency rate is determined in WD (17.430% at 30°C). In addition, while the maximum exergy efficiency rate of CC is calculated as 53.887% at 10°C, COGEN is determined as 29.850% at 30°C. It is determined that the increase in exergy efficiency rates for all components is inversely proportional to the increase in dead state temperatures, but this relationships is directly proportional for COGEN. According to exergy efficiency, it is necessary to focus on WD and GD, which have lowest efficiency rates.

- As there is a linear relationship between sustainability index "*SI*" and exergy efficiency rate "*ψ*", it is also seen with similar sustainability index of the relationship between exergy efficiency rates and dead state temperatures. Therefore, as seen in exergy efficiency rates, the highest sustainability index is obtained in GT (23.759 at 10°C), while the lowest sustainability index is determined in WD (1.211% at 30°C).

The exergy efficiency and sustainability index variations with dead state temperatures of components and COGEN are illustrated in Figure 5.3 and Figure 5.4.

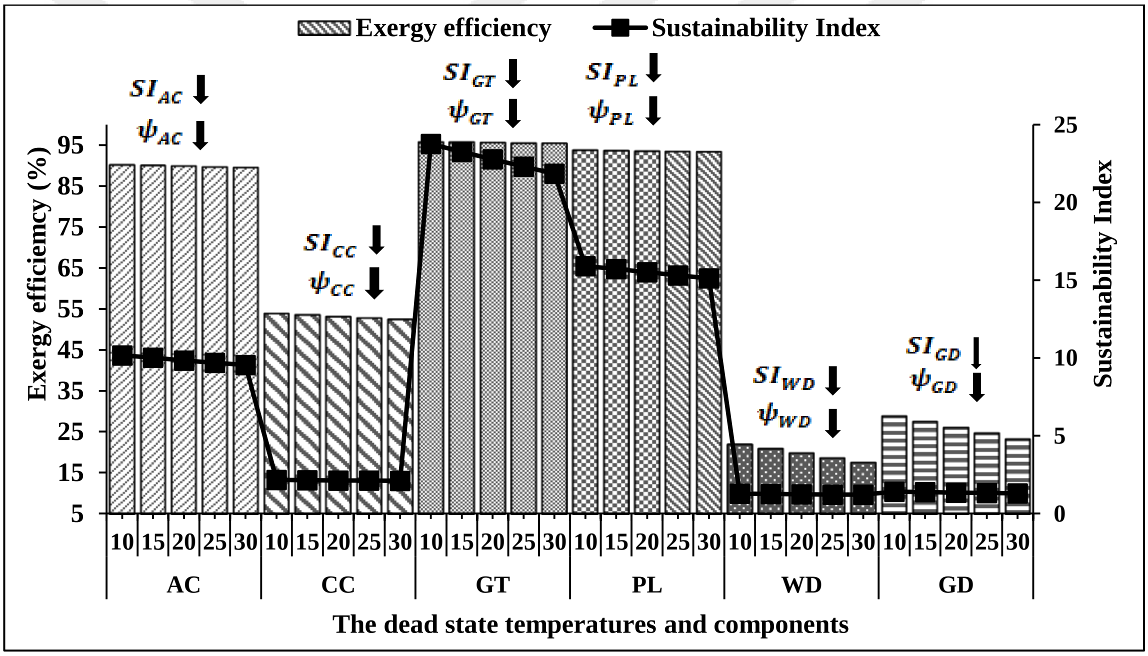


Figure 5.3. Effect of dead state temperatures on the exergy efficiency rates and sustainability index of components

Table 5.1. Results of conventional exergy analysis for COGEN and its components

Components	T(°C)	$\dot{E}_{x.F}$ (kW)	$\dot{E}_{x.P}$ (kW)	$\dot{E}_{x.D}$ (kW)	$\dot{E}_{x.L}$ (kW)	ψ (%)	SI (-)	ϕ (%)	φ (%)	θ (%)	$\dot{E}_X I\dot{P}$ (kW)
AC	10	7712.393	6954.122	758.271	-	90.168	10.171	3.808	2.676	8.995	74.553
	15		6942.349	770.044	-	90.015	10.015	3.868	2.721	9.140	76.888
	20		6928.896	783.497	-	89.841	9.843	3.935	2.773	9.304	79.596
	25		6917.073	795.320	-	89.688	9.697	3.994	2.818	9.449	82.013
	30		6905.249	807.144	-	89.534	9.555	4.054	2.863	9.592	84.475
CC	10	21125.355	11383.75	9741.605	-	53.887	2.169	48.927	34.374	115.564	4492.149
	15	21127.870	11307.13	9820.740	-	53.518	2.151	49.325	34.705	116.568	4564.876
	20	21130.464	11228.91	9901.554	-	53.141	2.134	49.730	35.045	117.584	4639.767
	25	21133.135	11153.09	9980.045	-	52.775	2.118	50.125	35.366	118.565	4713.079
	30	21135.882	11077.35	10058.532	-	52.410	2.101	50.519	35.682	119.537	4786.854
GT	10	12644.539	12112.393	532.146	-	95.791	23.759	2.673	1.878	6.313	22.398
	15	12656.924		544.531	-	95.698	23.245	2.735	1.924	6.463	23.426
	20	12668.322		555.929	-	95.612	22.789	2.792	1.968	6.602	24.394
	25	12680.822		568.429	-	95.517	22.306	2.855	2.014	6.753	25.483
	30	12693.352		580.959	-	95.423	21.848	2.918	2.061	6.904	26.591
PL	10	5768.259	5405.646	362.613	-	93.714	15.908	1.821	1.279	4.302	22.794
	15	5652.023	5292.390	359.633	-	93.637	15.716	1.806	1.271	4.269	22.883
	20	5530.720	5174.128	356.592	-	93.553	15.511	1.791	1.262	4.235	22.989
	25	5418.192	5064.573	353.619	-	93.473	15.321	1.776	1.253	4.201	23.081
	30	5307.265	4956.619	350.646	-	93.393	15.135	1.761	1.244	4.167	23.167
WD	10	3261.386	715.128	2546.258	-	21.927	1.281	12.789	8.985	30.206	1987.942
	15	3232.876	674.098	2558.778	-	20.851	1.263	12.851	9.042	30.372	2025.249
	20	3203.716	633.990	2569.726	-	19.789	1.247	12.906	9.095	30.516	2061.206
	25	3175.286	590.818	2584.468	-	18.607	1.229	12.980	9.159	30.704	2103.578
	30	3147.007	548.522	2598.485	-	17.430	1.211	13.051	9.218	30.881	2145.573
GD	10	4643.915	1336.047	3307.868	-	28.770	1.404	16.614	11.672	39.241	2356.196
	15	4593.810	1260.175	3333.635	-	27.432	1.378	16.743	11.781	39.569	2419.156
	20	4542.611	1183.468	3359.143	-	26.053	1.352	16.871	11.889	39.891	2483.983
	25	4492.527	1105.938	3386.589	-	24.617	1.327	17.009	12.001	40.233	2552.913
	30	4442.441	1027.599	3414.842	-	23.131	1.301	17.151	12.114	40.582	2624.953

Table 5.1. Results of conventional exergy analysis for COGEN and its components (continued)

Components	T(°C)	$\dot{E}_{x.F}$ **(kW)**	$\dot{E}_{x.P}$ **(kW)**	$\dot{E}_{x.D}$ **(kW)**	$\dot{E}_{x.L}$ **(kW)**	ψ **(%)**	SI **(-)**	ϕ **(%)**	φ **(%)**	θ **(%)**	$\dot{E}_{X}I\dot{P}$ **(kW)**
Total exergy destruction value of components	10	-	-	17248.770	-	-	-	-	60.864	204.622	-
	15	-	-	17387.360	-	-	-	-	61.353	206.266	-
	20	-	-	17526.440	-	-	-	-	61.843	207.916	-
	25	-	-	17668.480	-	-	-	-	62.345	209.601	-
	30	-	-	17810.610	-	-	-	-	62.846	211.287	-
Total exergy loss value of COGEN (Exhaust gases)	10	-	-	-	2661.680	-	-	-	9.392	31.575	-
	15	-	-	-	2485.547	-	-	-	8.770	29.486	-
	20	-	-	-	2306.225	-	-	-	8.138	27.359	-
	25	-	-	-	2133.445	-	-	-	7.528	25.309	-
	30	-	-	-	1964.099	-	-	-	6.930	23.300	-
COGEN	10	28340.033	8429.595	17248.770	2661.680	29.744	1.423	-	70.256	236.197	13988.286
	15	28297.786	8424.876	17387.360	2485.547	29.772	1.424		70.228	235.884	13956.345
	20	28253.484	8420.816	17526.440	2306.225	29.805	1.425		70.195	235.520	13921.539
	25	28219.292	8417.375	17668.480	2133.445	29.828	1.425		70.172	235.251	13895.407
	30	28189.273	8414.570	17810.610	1964.099	29.850	1.426		70.150	235.006	13871.958

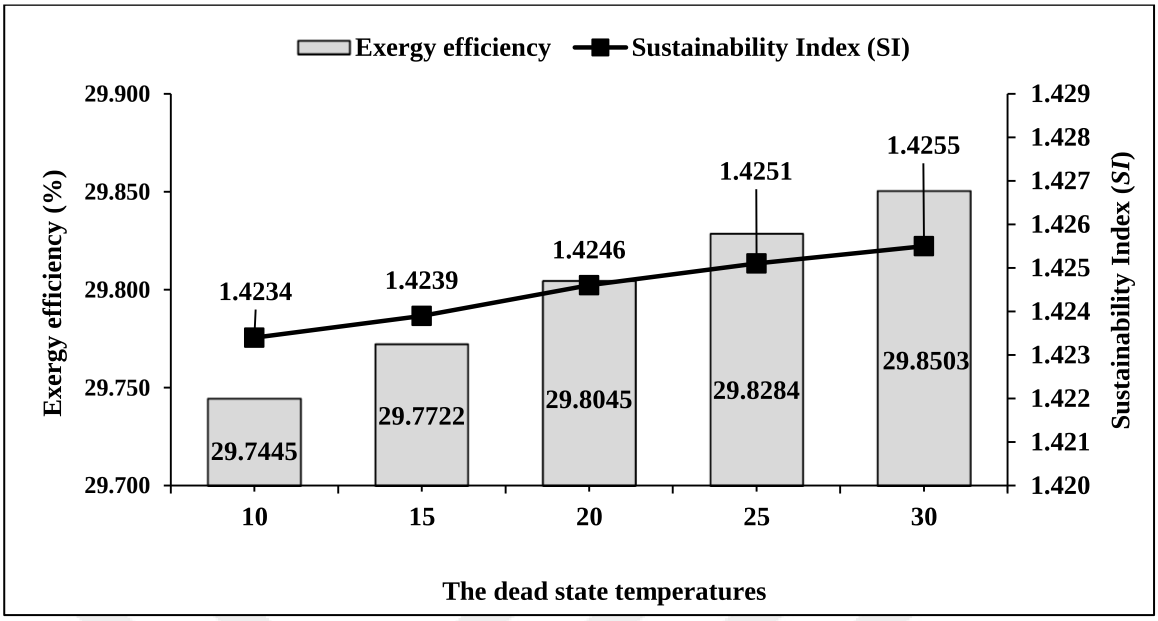


Figure 5.4. Effect of dead state temperatures on the exergy efficiency rates and sustainability index of COGEN

- The relative exergy consumption rate *"ϕ"* mentioned in Chapter 3.2.1 shows that the exergy consumption rate in each *k*th component is the total exergy consumption rate of the system. Accordingly, the highest relative exergy consumption rate is determined in CC, which has the highest exergy destruction value, while the lowest rate is calculated in PL, which also has a lowest exergy destruction value. As seen in Figure 5.5, the increase in relative exergy consumption rates of all component except PL are determined to be directly proportional to the increase in dead state temperatures, while for PL, this relationship is seen to be inversely proportional. The maximum relative exergy consumption rate of AC, CC, GT, WD and GD is calculated as 4.054%, 50.519%, 2.918, %13.051, %17.151 at 30°C dead state temperature, respectively; For PL, this rate is found as 1.821% at 10°C dead state temperature, respectively. The effects of dead state temperatures on the relative exergy consumption rates of components can be seen in Figure 5.5.

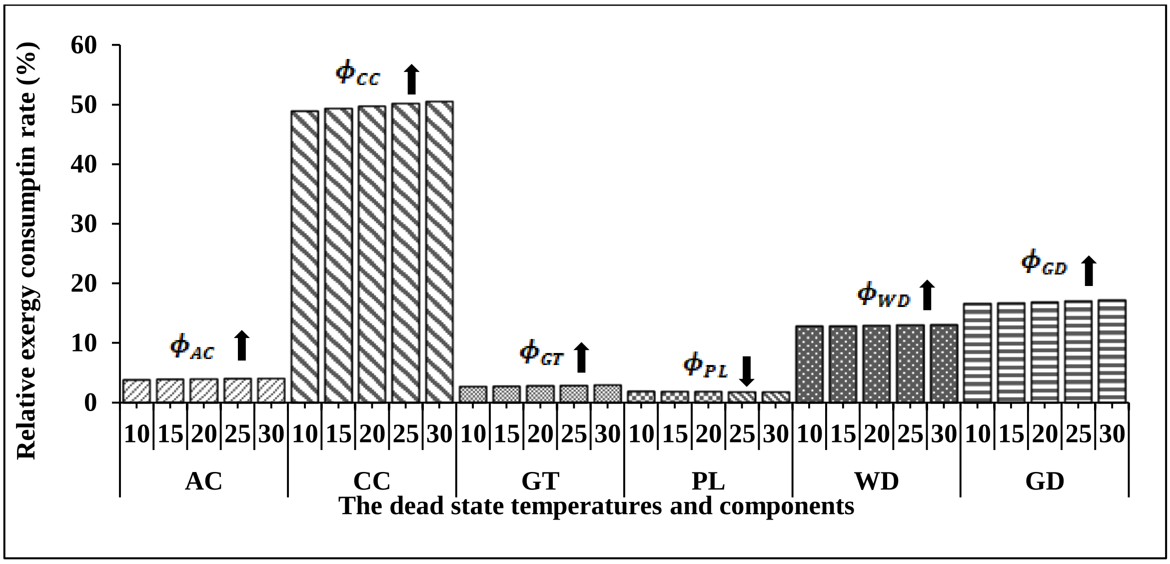


Figure 5.5. Effects of dead state temperatures on the relative exergy consumption rates of components

- The fuel exergy consumption rate *"φ"*, which is known as the ratio of exergy destruction value of the *k*th component to the total fuel exergy value entering the system, is determined as the highest value in CC where the highest exergy destruction value takes place, while the lowest value is determined in the PL where lowest exergy destruction value occurs among components. The effect of dead state temperature variations on exergy destruction values of the *k*th component and exergy change of the fuel entering the whole system affects the fuel exergy consumption rates. The increase in fuel exergy consumption rates of AC, CC, GT, WD and GD is directly proportional to the increase in dead state temperatures, while these rates of PL and COGEN are inversely proportional. The maximum fuel exergy consumption rate of AC, CC, GT, WD and GD is determined to be 2.863%, 35.682%, 2.061%, 9.218% and 12.114% at 30°C dead state temperature, while this rate is found as 1.279% and 70.256% at 10°C dead state temperature for PL and COGEN, respectively.
- The product exergy consumption rate *"θ"* defined as the ratio of exergy destruction value of the *k*th component to the product exergy value occurring in the system. As with the relative exergy rate and fuel exergy rate, the highest value of this rate is found in the CC with the highest exergy destruction value, the lowest value is in the PL with the lowest exergy destruction value among components. In addition, the increase in product exergy consumption rates of AC, CC, GT, WD and GD is directly

proportional to the increase in dead state temperatures, while inversely proportional to COGEN and PL. The maximum product exergy consumption rate of AC, CC, GT, WD and GD is found as 9.592%, 119.537%, 6.904%, 30.881% and 40.582%, at 30°C dead state temperature, while this rate is calculated as 4.302% at 10°C dead state temperature for PL. On the other hand, the maximum and minimum product exergy consumption rate of the COGEN is determined to be 236.197% and 235.006% at 10°C and 30°C dead state temperatures, respectively. The fuel and product exergy consumption rates of components and COGEN are illustrated in Figure 5.6 and Figure 5.7.

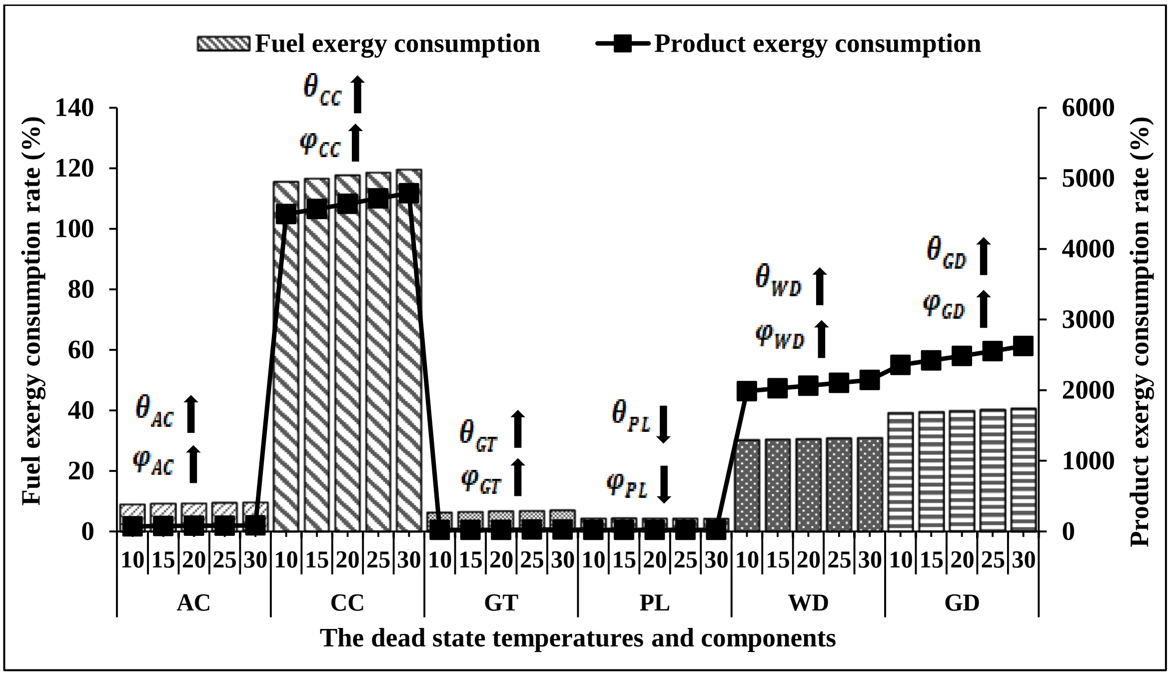


Figure 5.6. Effects of dead state temperatures on the fuel and product exergy consumption rate of components

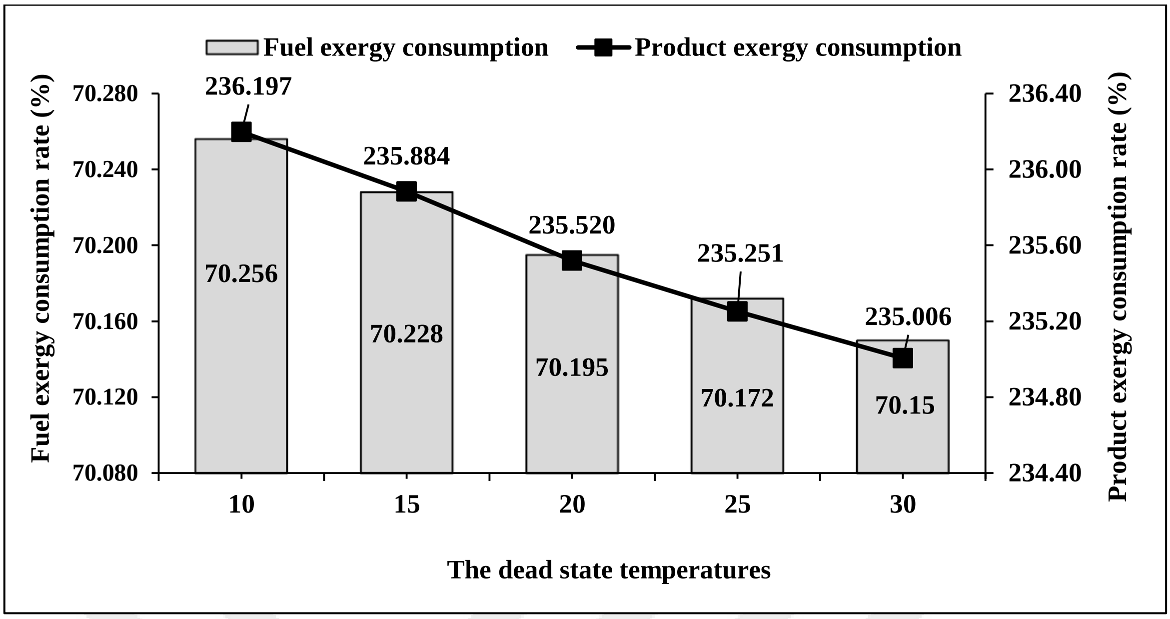


Figure 5.7. Effects of dead state temperatures on the fuel and product exergy consumption rate of COGEN

- The exergy improvement potential *"*$\dot{E}xI\dot{P}_k$*"*, which shows the amount of exergy consumption that can be recovered with the help of the improvements made in the components of the system, is directly proportional to the exergy destruction value, while it is inversely proportional to the exergy efficiency. According to this assessment, CC, WD and GD have the highest exergy improvement potential compared to other components, since the value of exergy destruction is higher than other component. The increase in exergy improvement potential values of all components is directly proportional to the increase in dead state temperatures, while this value increase in COGEN is inversely proportional. The main reason for this is that the amount of exergy losses value occurring in the COGEN is high. For AC, CC, GT PL, WD and GD, the maximum exergy improvement potential is calculated as 84.476 kW, 4786.854 kW, 26.591 kW, 23.167 kW, 2145.573 kW and 2624.953 kW at 30°C dead state temperature. Also the maximum and minimum exergy improvement potential value of the COGEN are calculated as 13988.286 kW and 13871.958 kW at 10°C and 30°C dead state temperatures, respectively. The exergy improvement potential values of components and COGEN are given in Figure 5.8 and Figure 5.9, respectively.

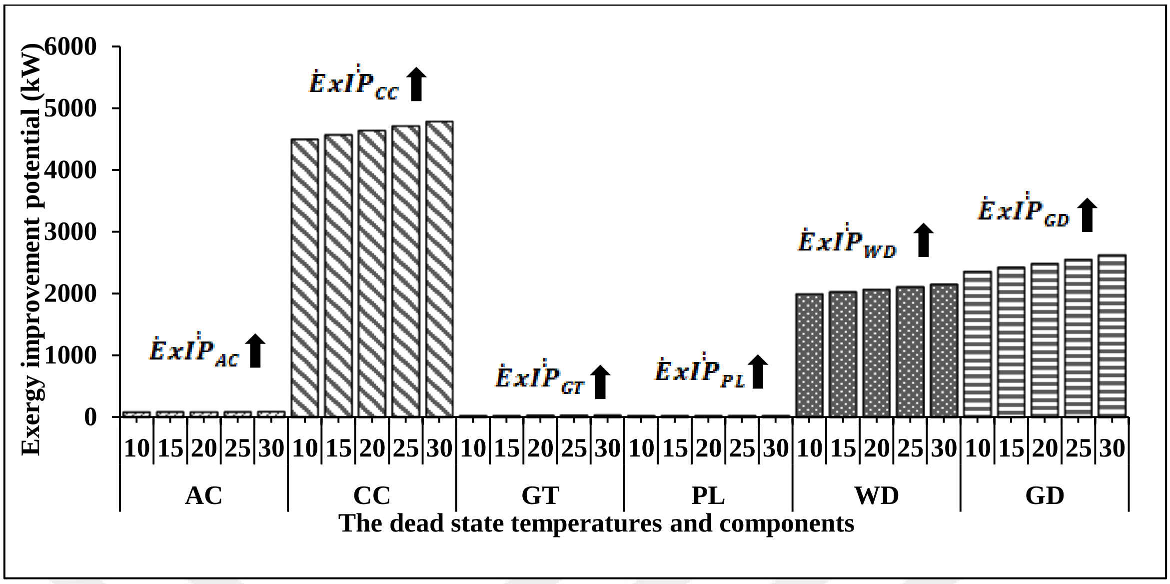


Figure 5.8. Effects of dead state temperatures on the exergy improvement potential values of components

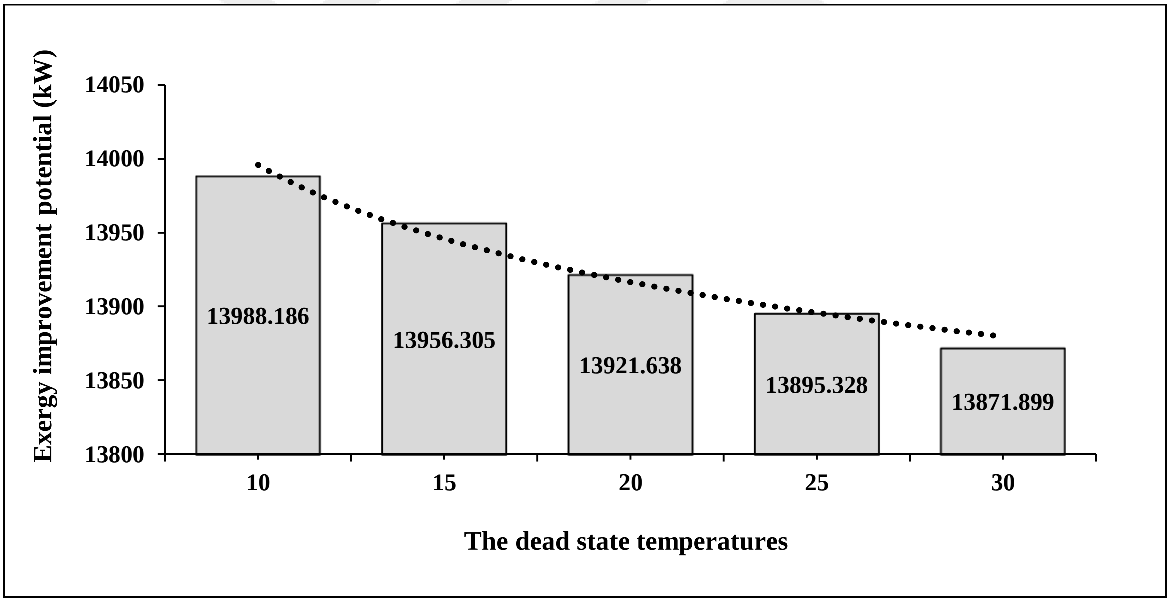


Figure 5.9. Effects of dead state temperatures on the exergy improvement potential values of COGEN

5.2. Evaluation of the System in terms of Exergoeconomic Analysis

The exergoeconomic analysis of the components in the COGEN system using the SPECO and EXCEM method is examined for five different dead state temperatures. The unit fuel exergy cost “c_f” and the unit product exergy cost “c_p”, the exergy destruction cost “$\dot{C}_D$”,, the exergoeconomic factor “f_k” and relative cost difference “r_k” of *k*th component are calculated using the exergy value, the cost per unit of exergy and the exergy cost rate of stream points (Table 4.12). In addition, the exergoeconomic factor “$\dot{R}_{ex}$” known as the capital cost per unit sum of exergy destruction and exergy loss is determined. During this analysis, it enables us to obtain faster and more accurate results by using the cost balance equations and auxiliary equations of the components shown in Table 4.11. All the results of the above-mentioned exergoeconomic analysis are given in Table 5.2.

According to the information obtained from this table, the following comments can be made:

- Unit cost per unit of fuel exergy “c_f” entering each component in the system is calculated and compared. According to these data, AC has the highest unit fuel exergy cost rate (17.612 $/GJ at a 30°C), while CC has a lowest value (6.970 $/GJ at between 10°C -30°C), In addition, the maximum unit fuel exergy cost rates of GT, PL, WD and GD are calculated as 16.241 $/GJ, 16.241 $/GJ, 13.214 $/GJ and 12.036 $/GJ at 30°C dead state temperature, respectively. According to these results, the unit fuel exergy cost rate of CC does not change as natural gas is considered the unit fuel exergy cost rate constant. Therefore, the increase in unit fuel exergy cost rate of all components except CC is directly proportional to the increase in dead state temperatures.
- For all components, the increase in unit product exergy cost rates “c_P” is directly proportional to the increase in dead state temperatures. The maximum unit fuel cost rates of AC, CC, GT, PL, WD and GD are found to be 20.931 $/GJ, 13.344 $/GJ, 17.612 $/GJ, 17.598 $/GJ, 78.022 $/GJ and 53.696 $/GJ at 30°C dead state temperature, respectively. According to these results, WD and GD have highest unit product exergy cost rates, while CC have lowest unit product exergy cost rates. The unit fuel exergy cost rates and unit product cost rates of components are illustrated in Figure 5.10.

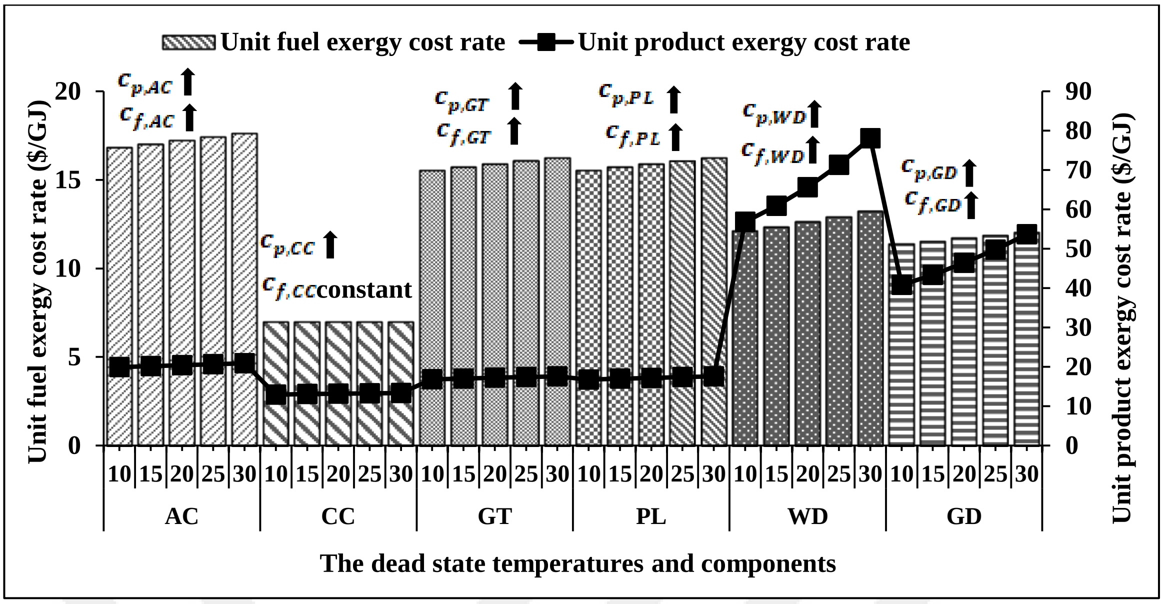


Figure 5.10. Effect of dead state temperatures on the unit fuel exergy and unit product fuel cost rates of components

Table 5.2. Result of exergoeconomic analysis for COGEN and its components

Components	T(°C)	$\dot{E}_{x.D}$ (GJ/h)	$\dot{E}_{x.L}$ (GJ/h)	c_f ($/GJ)	c_P ($/GJ)	$\dot{C}_D$ ($/h)	$\dot{C}_L$ ($/h)	$\dot{Z}$ ($/h)	$\dot{Z}+\dot{C}_D+\dot{C}_L$ ($/h)	f (%)	r (%)	$\dot{R}_{ex}$ (GJ/$)
AC	10	2.730	-	16.813	19.898	45.899	-	31.324	77.223	40.563	18.349	0.087
	15	2.772	-	17.009	20.149	47.149	-		78.473	39.917	18.461	0.088
	20	2.821	-	17.215	20.418	48.564	-		79.888	39.210	18.606	0.090
	25	2.863	-	17.414	20.675	49.856	-		81.180	38.586	18.726	0.091
	30	2.906	-	17.612	20.931	51.180	-		82.504	37.967	18.845	0.093
CC	10	35.070	-	6.970	12.978	244.438	-	1.780	246.218	0.723	86.198	19.702
	15	35.355	-	6.970	13.068	246.424	-		248.204	0.717	87.489	19.862
	20	35.646	-	6.970	13.160	248.453	-		250.233	0.711	88.809	20.026
	25	35.928	-	6.970	13.251	250.418	-		252.198	0.706	90.115	20.184
	30	36.211	-	6.970	13.344	252.391	-		254.171	0.700	91.449	20.343
GT	10	1.916	-	15.538	16.813	29.771	-	25.835	55.606	46.461	8.206	0.074
	15	1.960	-	15.710	17.009	30.792	-		56.627	45.623	8.269	0.076
	20	2.001	-	15.894	17.215	31.804	-		57.639	44.822	8.311	0.077
	25	2.046	-	16.067	17.414	32.873	-		58.708	44.006	8.384	0.079
	30	2.091	-	16.241	17.612	33.960	-		59.795	43.206	8.442	0.081
PL	10	1.305	-	15.539	16.773	20.278	-	3.712	23.990	15.473	7.941	0.352
	15	1.295	-	15.710	16.972	20.344	-		24.056	15.431	8.033	0.349
	20	1.284	-	15.893	17.188	20.407	-		24.119	15.390	8.148	0.346
	25	1.273	-	16.067	17.391	20.453	-		24.165	15.361	8.240	0.343
	30	1.262	-	16.241	17.598	20.496	-		24.208	15.334	8.355	0.340

Table 5.2. Result of exergoeconomic analysis for COGEN and its components (continued)

Components	T(°C)	$\dot{E}_{x.D}$ (GJ/h)	$\dot{E}_{x.L}$ (GJ/h)	c_f (\$/GJ)	c_P (\$/GJ)	$\dot{C}_D$ (\$/h)	$\dot{C}_L$ (\$/h)	$\dot{Z}$ (\$/h)	$\dot{Z}+\dot{C}_D+\dot{C}_L$ (\$/h)	f (%)	r (%)	$\dot{R}_{ex}$ (GJ/\$)
WD	10	9.167	-	12.102	56.852	110.939	-	4.313	115.252	3.742	369.774	2.125
	15	9.212	-	12.332	60.940	113.602	-		117.915	3.658	394.162	2.136
	20	9.251	-	12.617	65.653	116.720	-		121.033	3.563	420.353	2.145
	25	9.304	-	12.897	71.342	119.994	-		124.307	3.470	453.167	2.157
	30	9.355	-	13.214	78.022	123.617	-		127.930	3.371	490.450	2.169
GD	10	11.908	-	11.386	40.859	135.584	-	6.143	141.727	4.334	258.853	1.938
	15	12.001	-	11.530	43.382	138.372	-		144.515	4.251	276.253	1.954
	20	12.093	-	11.711	46.398	141.621	-		147.764	4.157	296.192	1.969
	25	12.192	-	11.870	49.754	144.719	-		150.862	4.072	319.158	1.985
	30	12.293	-	12.036	53.696	147.959	-		154.102	3.986	346.128	2.001
Total exergy destruction cost of COGEN	10	62.096	-	-	-	586.909	-	-	-	-	-	-
	15	62.595	-	-	-	596.683	-	-	-	-	-	-
	20	63.096	-	-	-	607.569	-	-	-	-	-	-
	25	63.606	-	-	-	618.313	-	-	-	-	-	-
	30	64.118	-	-	-	629.603	-	-	-	-	-	-
Total exergy loss cost of COGEN (Exhaust or unused gases)	10	-	9.582	-	-	-	398.199	-	-	-	-	-
	15	-	8.948	-	-	-	395.067	-	-	-	-	-
	20	-	8.302	-	-	-	391.766	-	-	-	-	-
	25	-	7.680	-	-	-	388.619	-	-	-	-	-
	30	-	7.071	-	-	-	385.496	-	-	-	-	-
COGEN	10	62.096	9.582	-	-	586.909	398.199	73.107	1058.215	6.909	97.092	-
	15	62.594	8.948	-	-	596.683	395.067		1064.857	6.865	98.315	-
	20	63.095	8.302	-	-	607.569	391.766		1072.442	6.817	99.586	-
	25	63.607	7.680	-	-	618.313	388.619		1080.039	6.769	100.826	-
	30	64.118	7.071	-	-	629.603	385.496		1088.206	6.718	102.063	-

- The exergy destruction cost rate "$\dot{C}_D$" of any *k*th component is related to unit fuel exergy cost besides exergy destruction value. Accordingly, CC, which has lowest unit fuel exergy cost at all dead state temperatures among all components, has the highest exergy destruction cost because the exergy destruction rate is very high compared to other components. If the relationship between exergy destruction cost and dead state temperature variations is examined, while directly proportional relationship is observed in COGEN and its all components. The maximum and minimum exergy destruction cost are calculated to 51.180 \$/h and 45.899 \$/h for AC, 252.391 \$/h and 244.438 \$/h for CC, 33.960 \$/h and 29.771 \$/h for GT, 20.496 \$/h and 20.278 \$/h for PL, 123.617 \$/h and 110.939 \$/h for WD, 147.959 \$/h and 135.584 \$/h for GD and 629.603 \$/h and 586.909 \$/h for COGEN at the dead state temperatures of 30 °C and 10 °C, respectively. On the other hand the increase in exergy loss cost rates of COGEN is inversely proportional to the increase in dead state temperatures. The effect of dead state temperatures on exergy destruction cost of components and COGEN (including exergy loss rate) can be shown in Figure 5.11 and Figure 5.12, respectively.

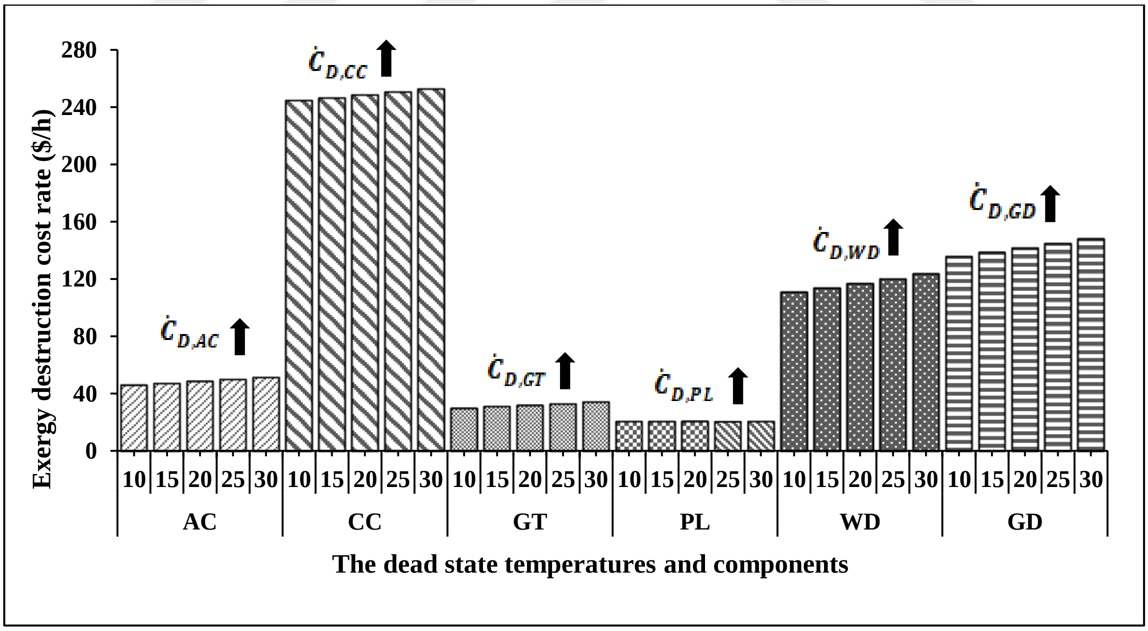


Figure 5.11. Effect of dead state temperatures on exergy destruction cost of components

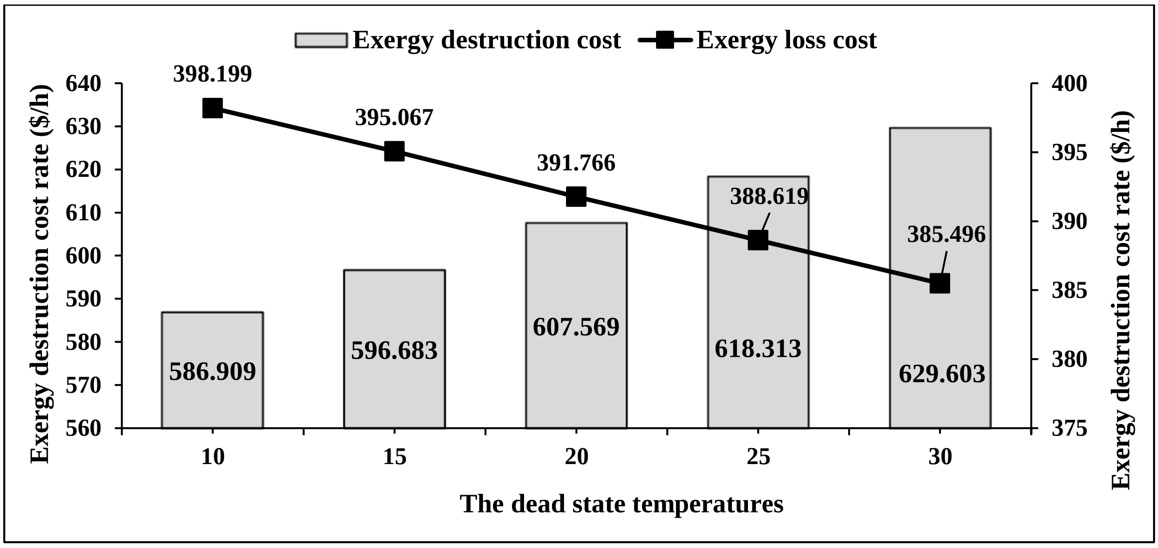


Figure 5.12. Effect of dead state temperatures on exergy destruction and loss cost of COGEN

- In GT, where the highest exergoeconomic factor “f” rate is observed between the components, the effect of its investment cost is higher than the other components. Besides, in CC, which has the lowest rate, it is due to its highest exergy destruction cost. For COGEN and its components, the increase in exergoeconomic factor rates is inversely proportional to the increase in dead state temperatures. The maximum exergoeconomic factor rates of AC, CC, GT, PL,WD, GD and COGEN are found as 40.563%, 0.723%, 46.461%, 15.473%, 3.742%, 4.334% and 6.909% at 10 °C dead state temperature.
- The increase in relative cost difference rates “r” of all components is directly proportional to the increase in dead state temperatures. The maximum relative cost difference rates of AC, CC, GT, PL, WD and GD are calculated as 18.845%, 91.449%, 8.442%, 8.355%, 490.450% and 346.128% at 30 °C dead state temperature. It is necessary to focus on WD and GD components, where the highest values are calculated. The exergoeconomic factor and the relative cost difference rate of components and COGEN are illustrated as Figure 5.13 and Figure 5.14, respectively.

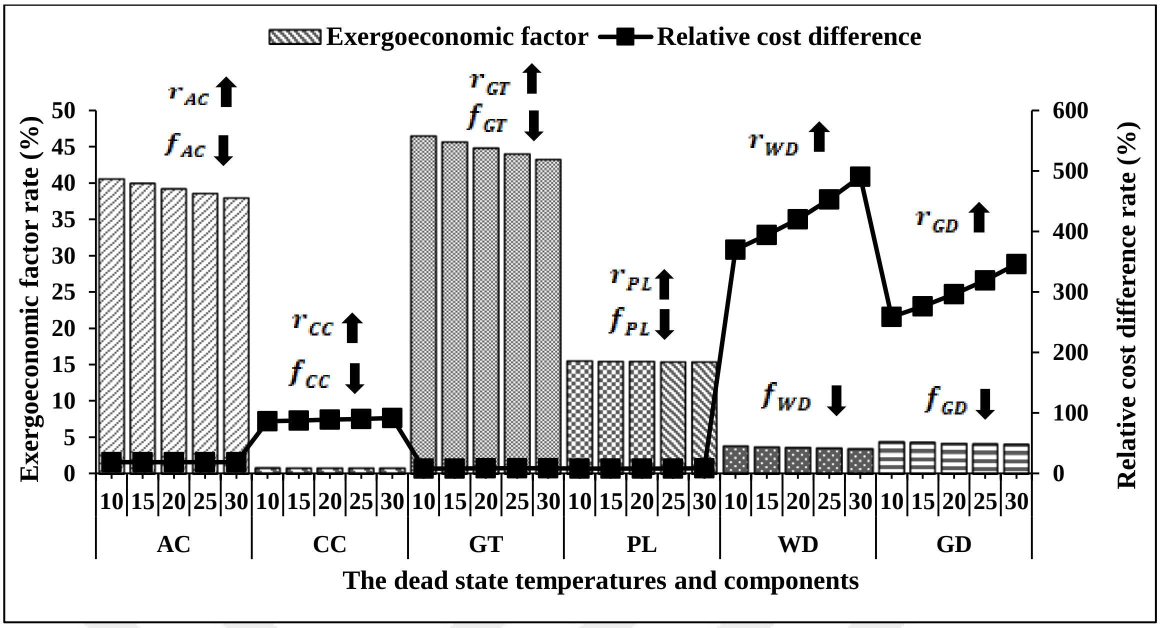


Figure 5.13. Effect of dead state temperatures on exergoeconomic factor and relative cost difference rates of components

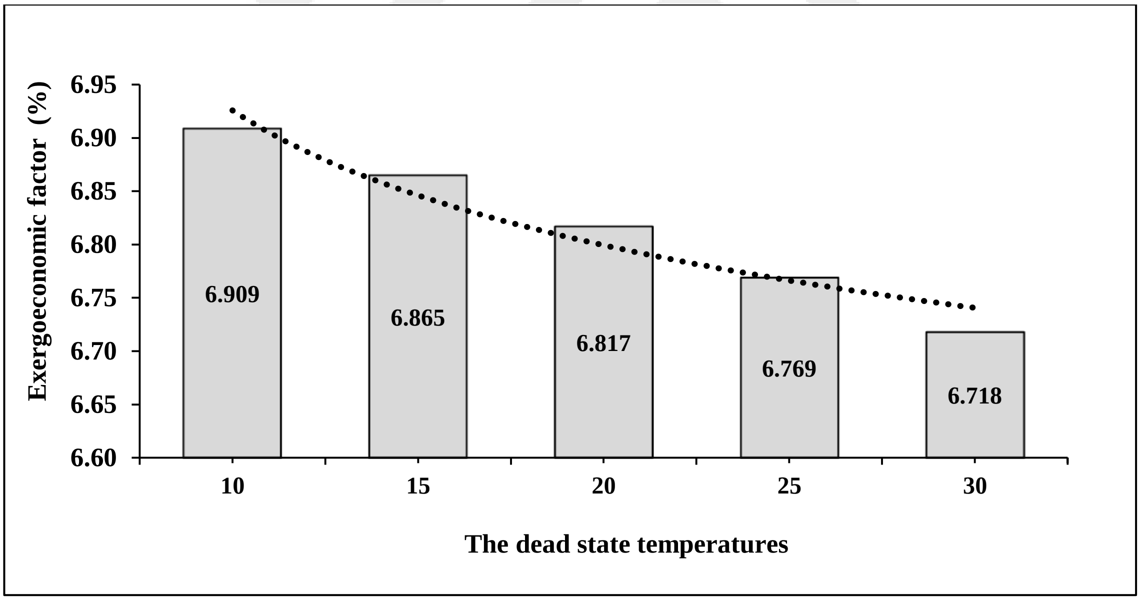


Figure 5.14. Effect of dead state temperatures on exergoeconomic factors of COGEN

- EXCEM, another method used to evaluate COGEN and its components in terms of exergoeconomic analysis, is indicated by exergetic cost parameters “$\dot{R}_{ex}$” which are determined by the rate of sum of exergy destruction and exergy loss to investment cost. The exergoeconomic results for COGEN and its components are shown in

Figure 5.15 and Figure 5.16, respectively. While the increase in exergetic cost parameter of AC, CC, GT, WD and GD is directly proportional to increase in dead state temperatures, this relationship is determined inversely proportional for PL and COGEN. The maximum exergetic cost parameter are calculated as 0.093 GJ/$ for AC, 20.343 GJ/$ for CC, 0.081 GJ/$ for GT, 2.169 GJ/$ for WD and 2.001 GJ/$ for GD at 30°C dead state temperature, while this value is found as 0.352 GJ/$ for PL and 0.980 GJ/$ for COGEN at 10 °C dead state temperature. CC has the highest exergetic cost parameter between components because it has the highest exergy destruction value and lowest investment cost value. Therefore, in order to reduce CC's exergy destruction, improvements must be made in the working conditions and design of the component.

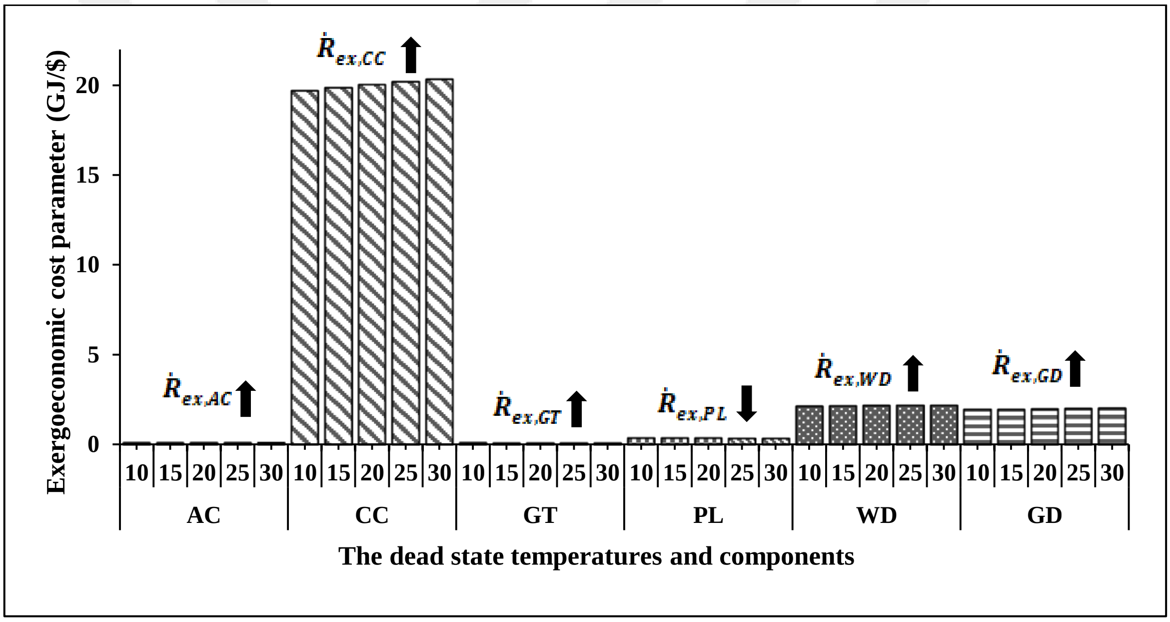


Figure 5.15. Effect of dead state temperatures on exergoeconomic cost parameters of components

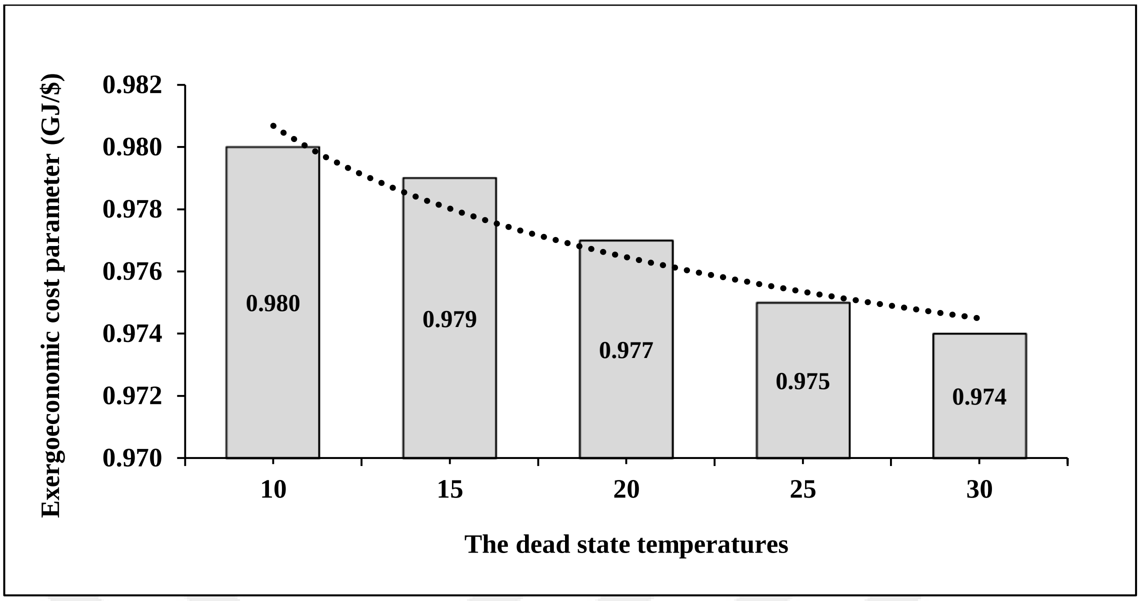


Figure 5.16. Effect of dead state temperatures on exergoeconomic cost parameters of COGEN

5.3. Evaluation of the System in terms of Exergoenvironmental Analysis

The system and components are examined for five different temperatures in terms of environmental analysis and the results are tabulated in Table 5.3 are obtained using the environmental impact balance equations given in Table 4.14 and the environmental impact of stream points in COGEN shown in Table 4.15. Thus, the environmental impact of exergy loss and destruction on COGEN and its components is determined, while the exergoenvironmental factor rate “f_b” and the relative difference of the environmental impact rate “r_b” of components are compared with each other. If the exergoenvironmental results shown in Table 5.3 are examined in detail, the following comments can be made:

- Among the components, for all dead state temperatures, the highest unit fuel environmental impact rate “b_f” is determined in AC, while the lowest rates are observed in CC. The increase in unit fuel environmental impact rates of CC is inversely proportional to the increase in dead state temperatures, whereas all components except CC this relationship is directly proportional. The maximum unit fuel environmental impact rate for AC, GT, PL, WD and GD are calculated as 7222.280 mPts/GJ, 6891.169 mPts/GJ, 6891.170 mPts/GJ, 5549.409 mPts/GJ and 5106.257 mPts/GJ at the dead state temperature of 30°C, respectively, while this rate is found as 2942.660 mPts/GJ at 10°C for CC.

- The increase in unit product environmental impact rates “b_p” of all components are determined to be directly proportional to the increase in dead state temperatures. The maximum and minimum unit product environmental impact rate are calculated as 8066.760 mPts/GJ and 7637.809 mpts/GJ for AC, 6169.566 mPts/GJ and 6003.495 mPts/GJ for CC, 7222.280 mPts/GJ and 6886.640 mPts/GJ for GT, 7378.970 mPts/GJ and 7039.380 mPts/GJ for PL, 32542.325 mPts/GJ and 23842.054 mPts/GJ for WD, 22506.529 mPts/GJ and 17168.925 mPts/GJ for GD at 30 °C and 10 °C dead state temperatures, respectively. For all dead state temperatures, WD and GD are determined to have a highest unit product environmental impact rate between components. The results of unit fuel environmental impact rates and unit product environmental impact rates of components are illustrated as Figure 5.17.

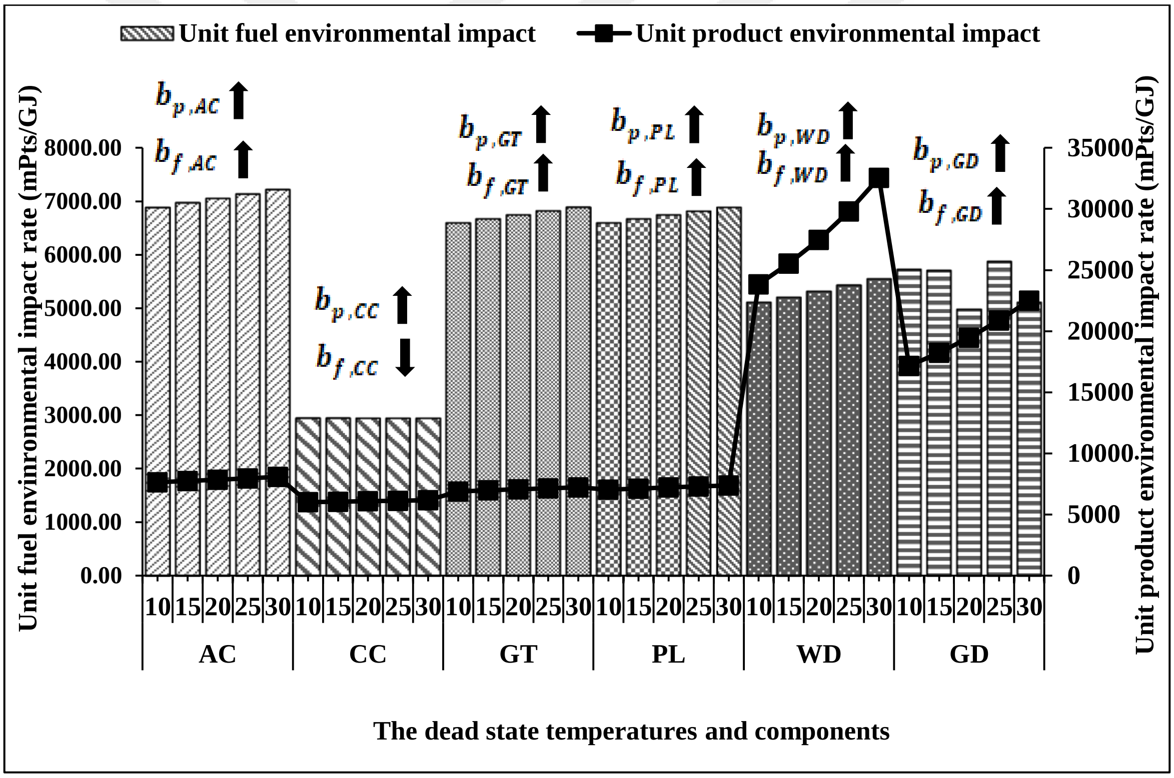


Figure 5.17. Effect of dead state temperatures on environmental impact rates of components

Table 5.3. Result of exergoenvironmental analysis for COGEN and its components

Components	T **(°C)**	b_f **(mPts/GJ)**	b_p **(mPts/GJ)**	$\dot{B}_D$ **(mPts/h)**	$\dot{B}_L$ **(mPts/h))**	$\dot{Y}$ **(mPts/h)**	$\dot{B}^{PF}$ **(mPts/h)**	$\dot{Y} + \dot{B}_D + \dot{B}_L + \dot{B}^{PF}$ **(mPts/h)**	f_b **(%)**	r_b **(%)**
AC	10	6886.640	7637.809	18800.527	-	4.992	-	18805.519	0.0265	10.908
	15	6968.660	7741.761	19317.126	-			19322.118	0.0258	11.094
	20	7055.500	7853.630	19903.566	-			19908.558	0.0251	11.312
	25	7138.660	7959.916	20437.984	-			20442.976	0.0244	11.504
	30	7222.280	8066.760	20987.946	-			20992.938	0.0238	11.693
CC	10	2942.660	6003.495	103199.086	-	15.512	22221.482	125436.080	17.7277	104.016
	15	2942.310	6044.198	104025.370	-			126262.364	17.6117	105.424
	20	2941.950	6086.113	104868.750	-			127105.744	17.4949	106.873
	25	2941.580	6127.605	105685.086	-			127922.080	17.3832	108.310
	30	2941.200	6169.566	106503.793	-			128740.787	17.2727	109.764
GT	10	6596.292	6886.640	12638.495	-	28.694	-	12667.189	0.2265	4.402
	15	6668.268	6968.660	13069.805	-			13098.499	0.2191	4.505
	20	6745.306	7055.500	13497.357	-			13526.051	0.2121	4.599
	25	6818.087	7138.660	13949.806	-			13978.500	0.2053	4.702
	30	6891.169	7222.280	14409.434	-			14438.128	0.1987	4.805
PL	10	6596.290	7039.380	8608.158	-	7.722	-	8615.880	0.0896	6.717
	15	6668.270	7121.560	8635.410	-			8643.132	0.0893	6.798
	20	6745.300	7210.680	8660.965	-			8668.687	0.0891	6.899
	25	6818.090	7294.170	8679.429	-			8687.151	0.0889	6.983
	30	6891.170	7378.970	8696.657	-			8704.379	0.0887	7.079

Table 5.3. Result of exergoenvironmental analysis for COGEN and its components (continued)

Components	T (°C)	b_f (mPts/GJ)	b_P (mPts/GJ)	$\dot{B}_D$ (mPts/h)	$\dot{B}_L$ (mPts/h)	$\dot{Y}$ (mPts/h)	$\dot{B}^{PF}$ (mPts/h)	$\dot{Y}+\dot{B}_D+\dot{B}_L+\dot{B}^{PF}$ (mPts/h)	f_b (%)	r_b (%)
WD	10	5112.776	23842.054	46868.818	-	109.486	1259.819	48238.123	2.8386	366.323
	15	5203.437	25528.483	47934.062	-			49303.367	2.7773	390.608
	20	5315.728	27465.197	49175.800	-			50545.105	2.7091	416.678
	25	5425.864	29803.644	50482.239	-			51851.544	2.6408	449.288
	30	5549.409	32542.325	51914.721	-			53284.026	2.5698	486.411
GD	10	4843.749	17168.925	57679.363	-	148.008	1444.383	59271.754	2.6866	254.455
	15	4902.721	18222.087	58837.555	-			60429.946	2.6351	271.673
	20	4975.986	19475.286	60174.599	-			61766.990	2.5781	291.385
	25	5039.774	20870.344	61444.925	-			63037.316	2.5261	314.113
	30	5106.257	22506.529	62771.217	-			64363.608	2.4741	340.764
Total exergy destruction environmental impact rates of COGEN	10	-	-	247794.447	-	-	-	-	-	-
	15	-	-	251819.328	-	-	-	-	-	-
	20	-	-	256281.037	-	-	-	-	-	-
	25	-	-	260679.469	-	-	-	-	-	-
	30	-	-	265283.768	-	-	-	-	-	-
Total exergy loss environmental impact rates of COGEN (Exhaust or unused gases)	10	-	-	-	157665.760	-	-	-	-	-
	15	-	-	-	156121.490	-	-	-	-	-
	20	-	-	-	154554.930	-	-	-	-	-
	25	-	-	-	153065.850	-	-	-	-	-
	30	-	-	-	151641.270	-	-	-	-	-
COGEN	10	-	-	247794.447	157665.760	314.413	24925.684	430700.304	5.8602	-
	15	-	-	251819.328	156121.490			433180.915	5.8267	-
	20	-	-	256281.037	154554.930			436076.064	5.7880	-
	25	-	-	260679.469	153065.850			438985.416	5.7496	-
	30	-	-	265283.768	151641.270			442165.135	5.7083	-

- CC, which has a lowest unit fuel environmental impact rate among components, has a highest exergy destruction environmental impact rate "$\dot{B}_D$" as the exergy destruction value is very high compared to other components. In addition, since PL has the lowest exergy destruction values among components at all dead state temperatures, the lowest exergy destruction environmental impact is experienced in this component. The increase in exergy destruction environmental impact rates of COGEN and its all components is found to be directly proportional to the increase in dead state temperatures. In addition, the increase in exergy loss environmental impact rates of COGEN is inversely proportional to the increase in dead state temperatures. The maximum exergy destruction environmental impacts of AC, CC, GT, PL, WD, GD and COGEN are found as 20987.946 mPts/h, 106503.793 mPts/h, 14409.434 mPts/h, 8696.657 mPts/h, 51914.721 mPts/h, 62771.217 mPts/h and 265283.768 mPts/h at 30°C dead state temperature, respectively. Also the maximum and minimum exergy loss environmental impact rates of COGEN are calculated as 157665.760 mPts/h and 151641.270 mPts/h at 30°C and 10°C dead state temperatures, respectively. The exergy destruction environmental impact rates of all components and COGEN (with exergy loss environmental impact) for five dead state temperatures are given Figure 5.18 and Figure 5.19, respectively.

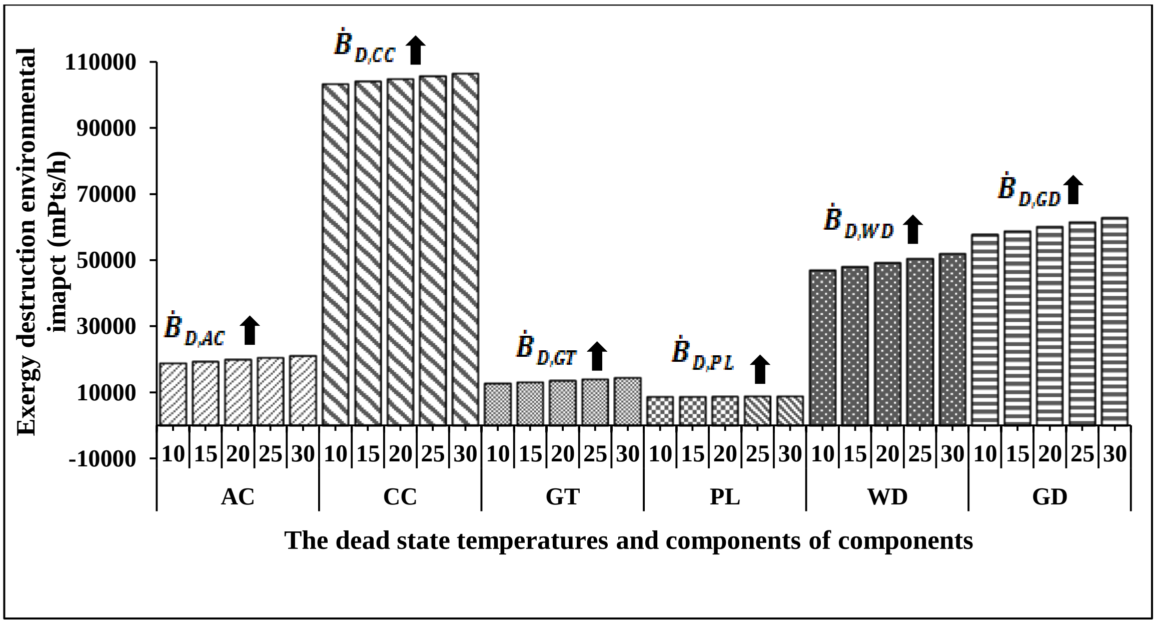


Figure 5.18. Effect of dead state temperatures on exergy destruction cost of components

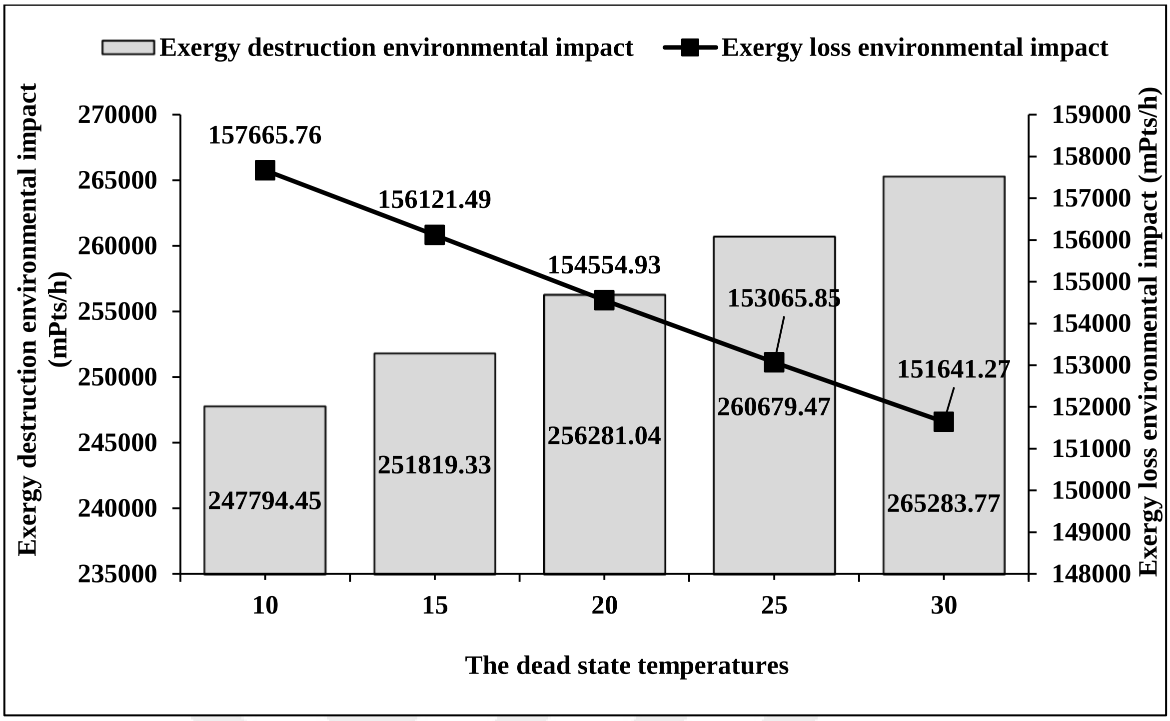


Figure 5.19. Effect of dead state temperatures on exergy destruction cost of COGEN

- For AC, GT and PL, the ratio of component-related environmental impact rate“$\dot{Y} + \dot{B}^{PF}$” to total environmental impact rate “$\dot{Y} + \dot{B}^{PF} + \dot{B}_D + \dot{B}_L$” is found to be very low. In other words, component-related environmental impact rate is determined to be negligible. In this study, exergoenvironmental factor “f_b” is calculated for all components and COGEN and the effects of dead state temperatures are investigated by taking this value into account. The increase in exergoenvironmental factor rates of all components and COGEN are inversely proportional to the increase in dead state temperatures. The maximum exergoenvironmental factor rate is calculated as 0.0265% for AC, 17.7277% for CC, 0.2265% for GT, 0.0896% for PL, 2.8386% for WD, 2.6866% for GD and 5.8602% for COGEN at 10°C dead state temperature, respectively.
- For a component, the relative environmental impact difference “r_b”, which describes the relative increase in unit product environmental impact rate compared to unit fuel environmental impact, is important for environmental evaluation and optimization of the component. WD and GD which have the highest relative environmental impact difference rate compared to other components, are the components to focus on. The increase in relative environmental impact difference rate of COGEN and its all

components is directly proportional to the increase in dead state temperatures. The maximum relative environmental impact difference rates of AC, CC, GT, PL, WD and GD are calculated as 11.693%, 109.764%, 4.805%, 7.076%, 486.411% and 340.764% at 30°C, respectively. The exergoenvironmental factor rate and the relative environmental impact difference rate of all components is shown is Figure 5.20, while the exergoenvironmental factor of COGEN is illustrated in Figure 5.21.

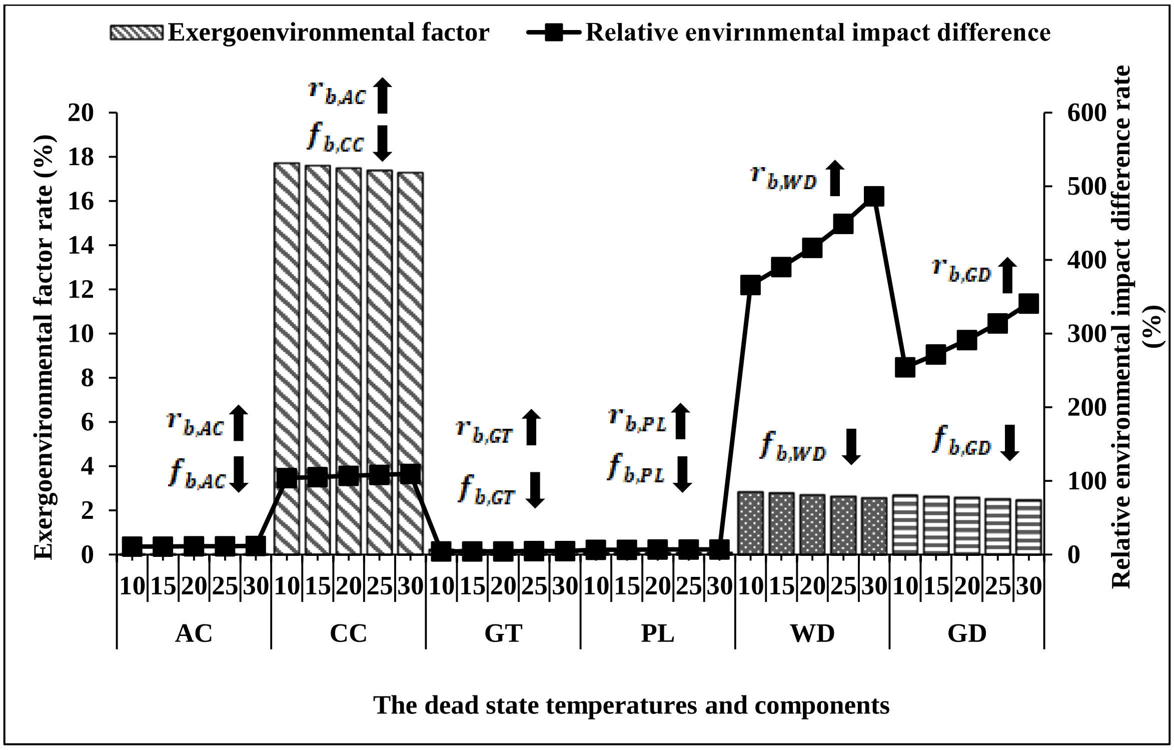


Figure 5.20. Effect of dead state temperatures on exergoenvironmental factor and relative environmental impact difference rates of components

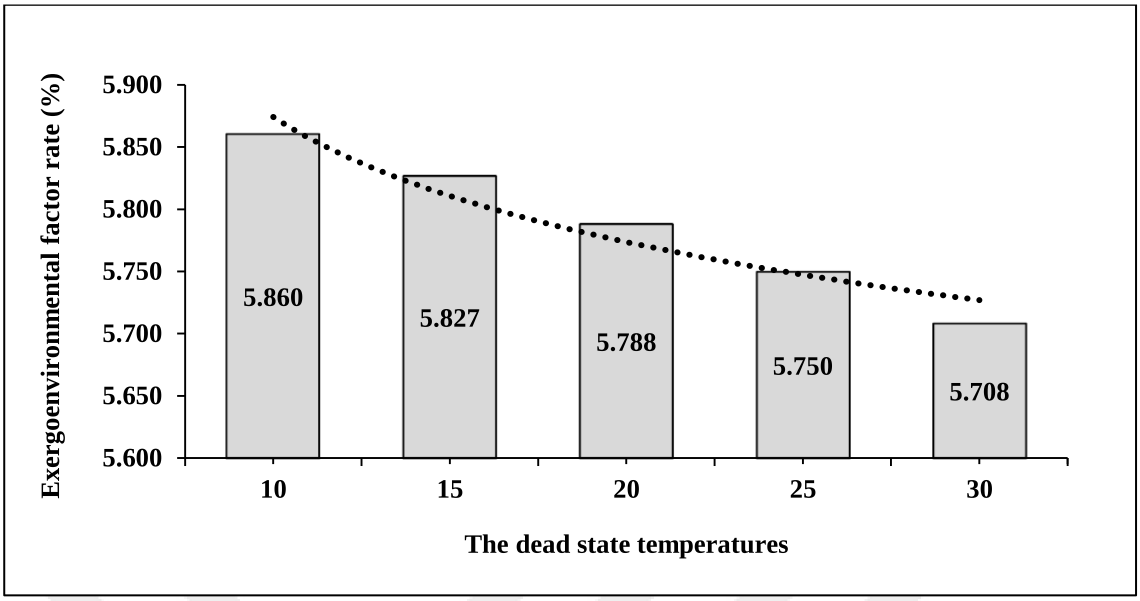


Figure 5.21. Effect of dead state temperatures on exergoenvironmental factors of COGEN

5.4. Evaluation of the System in terms of Advanced Exergy Analysis

In chapter 4.1, the real, theoretical and unavoidable working conditions of the components are presented. According to these conditions, the endogenous and exogenous exergy destruction values that reveal the effects of these components on each other are determined, also unavoidable and avoidable exergy destruction values that reveal the effect of technological constraints and production processes on exergy destruction value are determined. According to the advanced exergy method described in chapter 3.5, an advanced exergy analysis of the system has been performed and is presented in Table 5.4. These results can be interpreted as follows, respectively;

- The endogenous exergy destruction value "$\dot{E}x_D^{EN}$" of all other components in the system except PL is found to be relatively higher than the exogenous exergy destruction value "$\dot{E}x_D^{EX}$" of these components. This again indicates that the relationship between all components except PL is weak. In other words, most of the reasons for the irreversibility of these components are due to the operating conditions within them. In CC where combustion reactions occur, it has the highest exergy destruction value among the components, as well as the highest endogenous exergy destruction value (6357.772 kW at 30°C). Additionally, the exogenous destruction value of WD and GD is found to be negative. The main reason for this is that the temperature and mass of exhaust gas obtained from the gas turbine unit, which is assumed to operate under theoretical conditions, is very low. Therefore, the ratio of fuel needed by WD and GD increased and the irreversibility increased as a result of combustion reactions. The increase in endogenous and exogenous exergy destruction values of AC, CC and GT are seen to be directly proportional to the increase in dead state temperatures, whereas for PL this relationship is found to be inversely proportional to both parts of exergy destruction values. In addition, the increase in endogenous exergy destruction values for WD, GD and COGEN is found to be directly proportional to the increase in dead state temperatures, while the increase in the exogenous exergy destruction values is found to be inversely proportional. The endogenous and exogenous exergy destruction rate of all components and COGEN are shown as Figure 5.22 and Figure 5.23, respectively.

Table 5.4. Results of advanced exergy analysis for COGEN and its components

Components	T (°C)	$\dot{E}x_D$ (kW)	$\dot{E}x_D^{EN}$ (kW)	$\dot{E}x_D^{EX}$ (kW)	$\dot{E}x_D^{UN}$ (kW)	$\dot{E}x_D^{AV}$ (kW)	$\dot{E}x_D^{UN}$(kW)		$\dot{E}x_D^{AV}$ (kW)		ε_{mod} (%)	y_D^{AV} (%)	x_D^{AV} (%)
							$\dot{E}x_D^{UN.EN}$ (kW)	$\dot{E}x_D^{UN.EX}$ (kW)	$\dot{E}x_D^{AV.EN}$ (kW)	$\dot{E}x_D^{AV.EX}$ (kW)			
AC	10	758.271	440.402	317.869	541.149	217.122	168.005	373.144	272.397	-55.275	28.634	1.579	28.634
	15	770.044	443.169	326.875	541.852	228.192	168.293	373.559	274.876	-46.684	29.634	1.594	29.634
	20	783.497	446.462	337.035	544.218	239.279	169.097	375.121	277.365	-38.086	30.540	1.608	30.540
	25	795.320	449.245	346.075	544.964	250.356	169.399	375.565	279.846	-29.490	31.479	1.622	31.479
	30	807.144	452.028	355.116	545.709	261.435	169.701	376.008	282.327	-20.892	32.390	1.637	32.390
CC	10	9741.605	6144.927	3596.678	7948.285	1793.320	5009.851	2938.434	1135.076	658.244	18.409	6.581	18.409
	15	9820.740	6198.025	3622.715	8049.872	1770.868	5071.591	2978.281	1126.434	644.434	18.178	6.531	18.178
	20	9901.554	6252.141	3649.413	8151.319	1750.235	5133.182	3018.137	1118.959	631.276	17.822	6.487	17.822
	25	9980.045	6304.937	3675.108	8248.135	1731.910	5191.661	3056.474	1113.276	618.634	17.491	6.454	17.491
	30	10058.532	6357.772	3700.760	8342.750	1715.782	5248.633	3094.117	1109.139	606.643	17.192	6.430	17.192
GT	10	532.146	303.797	228.349	84.695	447.451	48.350	36.345	255.447	192.004	84.085	1.481	84.085
	15	544.531	310.868	233.663	89.146	455.385	50.891	38.255	259.977	195.408	83.628	1.507	83.628
	20	555.929	317.374	238.555	92.565	463.364	52.843	39.722	264.531	198.833	83.350	1.534	83.350
	25	568.429	324.511	243.918	97.131	471.298	55.450	41.681	269.061	202.237	82.913	1.560	82.913
	30	580.959	331.663	249.296	101.723	479.236	58.072	43.651	273.591	205.645	82.491	1.586	82.491
PL	10	362.613	135.018	227.595	123.933	238.680	42.294	81.639	92.724	145.956	65.823	0.538	65.823
	15	359.633	133.682	225.951	123.203	236.430	41.879	81.324	91.803	144.627	65.743	0.532	65.743
	20	356.592	132.320	224.272	122.478	234.114	41.450	81.028	90.870	143.244	65.652	0.527	65.652
	25	353.619	130.986	222.633	121.757	231.862	41.035	80.722	89.951	141.911	65.568	0.521	65.568
	30	350.646	129.653	220.993	121.041	229.605	40.620	80.421	89.033	140.572	65.481	0.516	65.481

Table 5.4. Results of advanced exergy analysis for COGEN and its components (continued)

Compo nents	T **(°C)**	$\dot{Ex}_D$ **(kW)**	$\dot{Ex}_D^{EN}$ **(kW)**	$\dot{Ex}_D^{EX}$ **(kW)**	$\dot{Ex}_D^{UN}$ **(kW)**	$\dot{Ex}_D^{AV}$ **(kW)**	$\dot{Ex}_D^{UN}$**(kW)**		$\dot{Ex}_D^{AV}$ **(kW)**		ε_{mod} **(%)**	$y_D^{AV,EN}$ **(%)**	x_D^{AV} **(%)**
							$\dot{Ex}_D^{UN.EN}$ **(kW)**	$\dot{Ex}_D^{UN.EX}$ **(kW)**	$\dot{Ex}_D^{AV.EN}$ **(kW)**	$\dot{Ex}_D^{AV.EX}$ **(kW)**			
WD	10	2546.258	3531.170	-984.912	265.386	2280.872	178.258	87.128	3352.912	-1072.040	89.577	19.439	89.577
	15	2558.778	3559.249	-1000.471	293.411	2265.367	193.220	100.191	3366.029	-1100.662	88.533	19.515	88.533
	20	2569.726	3586.126	-1016.400	320.207	2249.519	206.408	113.799	3379.718	-1130.199	87.539	19.594	87.539
	25	2584.468	3616.322	-1031.854	350.468	2234.000	220.195	130.273	3396.127	-1162.127	86.439	19.689	86.439
	30	2598.485	3646.064	-1047.579	379.868	2218.617	232.017	147.851	3414.047	-1195.430	85.381	19.793	85.381
GD	10	3307.868	5011.971	-1704.103	705.265	2602.603	491.529	213.736	4520.442	-1917.839	78.679	26.207	78.679
	15	3333.635	5065.057	-1731.422	761.283	2572.352	521.063	240.220	4543.994	-1971.642	77.164	26.344	77.164
	20	3359.143	5118.507	-1759.364	817.699	2541.444	548.460	269.239	4570.047	-2028.603	75.657	26.495	75.657
	25	3386.589	5173.172	-1786.583	875.391	2511.198	573.908	301.483	4599.264	-2088.066	74.151	26.664	74.151
	30	3414.842	5228.645	-1813.803	933.892	2480.950	596.598	337.294	4632.047	-2151.097	72.652	26.854	72.652
COGEN	10	17248.761	15567.29	1681.48	9668.71	7580.05	5938.29	3730.43	9629.00	-2048.95	43.946	55.824	43.946
	15	17387.361	15710.05	1677.31	9858.77	7528.59	6046.94	3811.83	9663.11	-2134.52	43.299	56.022	43.299
	20	17526.441	15852.93	1673.51	10048.49	7477.96	6151.44	3897.05	9701.49	-2223.54	42.667	56.245	42.667
	25	17668.470	15999.17	1669.30	10237.85	7430.62	6251.65	3986.20	9747.53	-2316.90	42.056	56.511	42.056
	30	17810.608	16145.83	1664.78	10424.98	7385.63	6345.64	4079.34	9800.18	-2414.56	41.468	56.817	41.468

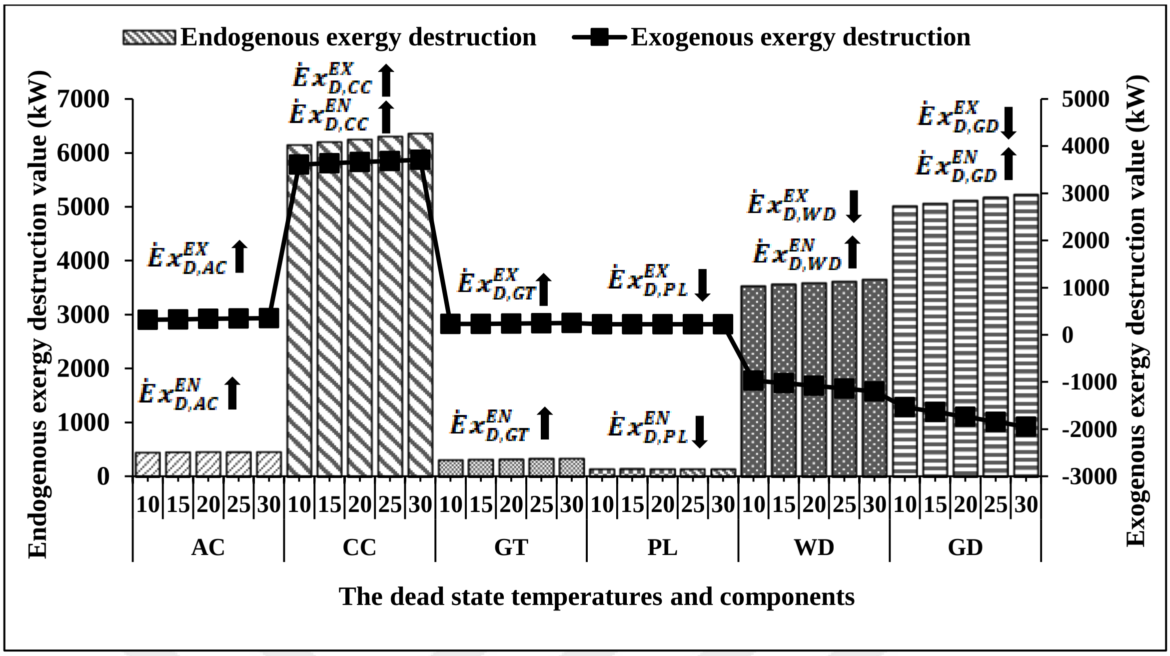


Figure 5.22. Effect of dead state temperatures on endogenous and exogenous exergy destruction value of components

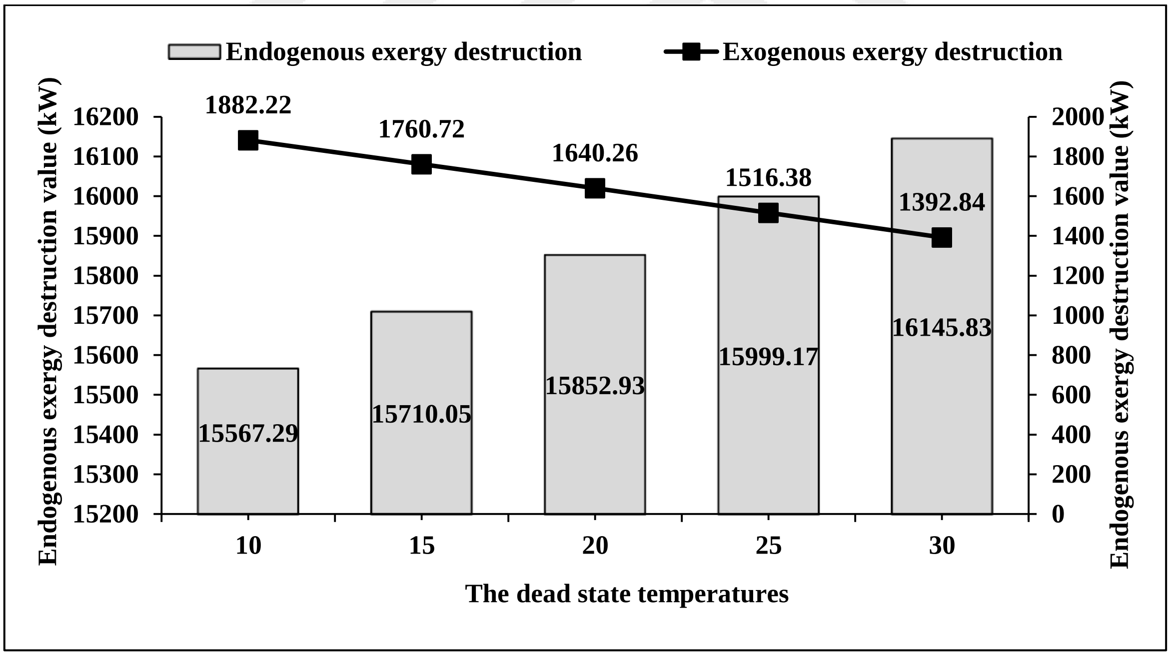


Figure 5.23. Effect of dead state temperatures on endogenous and exogenous exergy destruction value of COGEN

- Among the components in COGEN, the avoidable exergy destruction values “$\dot{E}x_D^{AV}$” of GT, PL, WD and GD are higher than the unavoidable exergy destruction values

“$\dot{E}x_D^{UN}$”, whereas the unavoidable exergy destruction values for AC and CC is higher at all dead state temperatures. In other words, these components (GT, PL, WD and GD), which have a higher ratio of avoidable exergy destruction value to exergy destruction value “x_D^{AV}”, need to be focused on these components because they have greater potential for improvement. The unavoidable exergy destruction value of COGEN is determined to be higher than avoidable exergy destruction value, mainly because CC's avoidable exergy destruction value accounts for 46% of total exergy destruction value at all dead state temperatures. Therefore, the combustion efficiency of CC in particular needs to be increased. It is determined that the increase in unavoidable and avoidable exergy destruction values of AC and GT are directly proportional to the increase in dead state temperatures, while for PL, this relationship is inversely proportional to both values. Furthermore, the increase in unavoidable exergy destruction values of CC, WD, GD and COGEN is directly proportional to the increase in dead state temperatures, while their avoidable exergy destruction values are inversely proportional. Additionally, the increase in “x_D^{AV}” of AC is directly proportional to the increase in dead state temperatures, while other components are inversely proportional. The unavoidable and avoidable exergy destruction values of all components and COGEN are shown as Figure 5.24 and Figure 5.25, respectively. In addition, the ratio of avoidable exergy destruction value to exergy destruction value “x_D^{AV}” is shown in Figure 5.26.

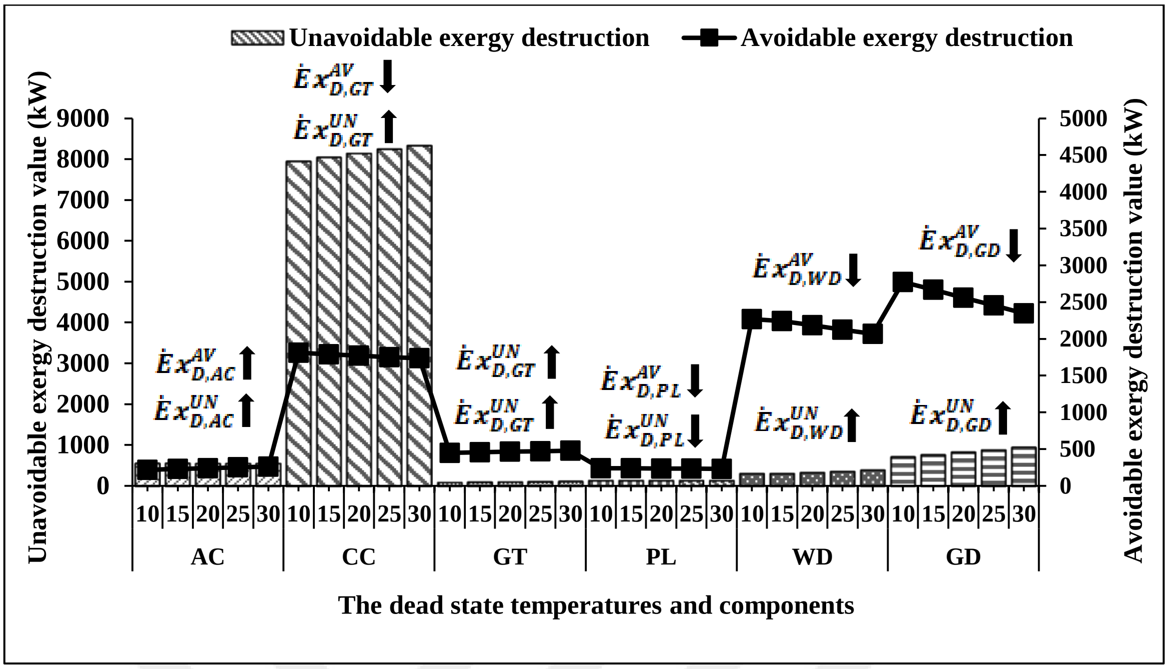


Figure 5.24. Effect of dead state temperatures on unavoidable and avoidable exergy destruction value of components

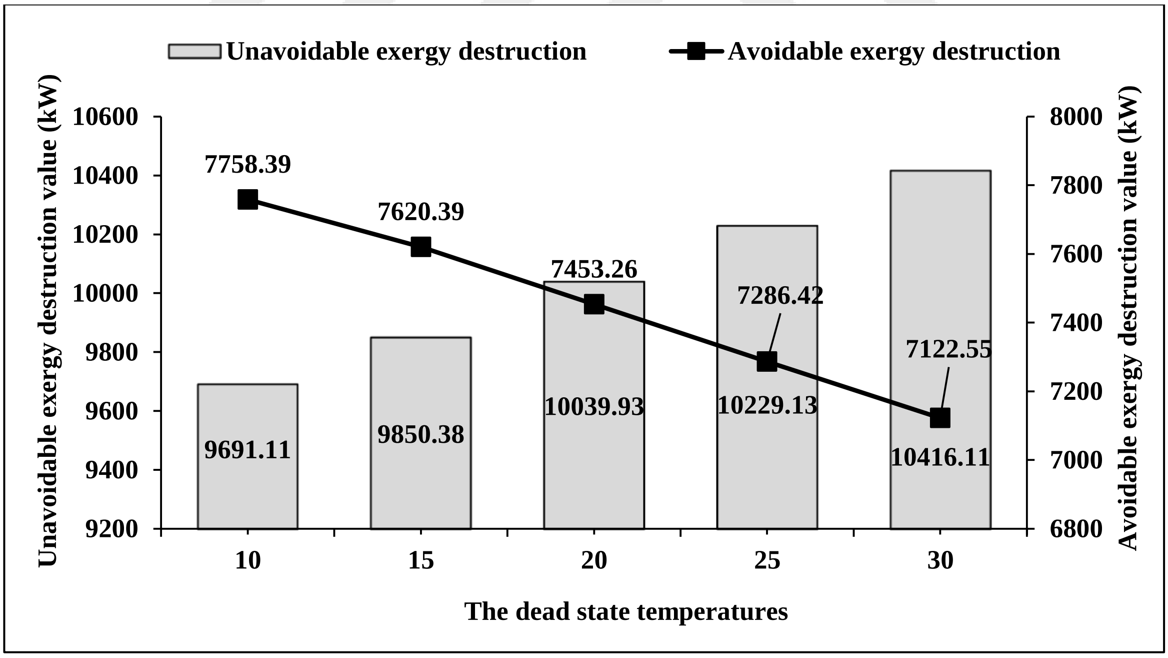


Figure 5.25. Effect of dead state temperatures on unavoidable and avoidable exergy destruction value of COGEN

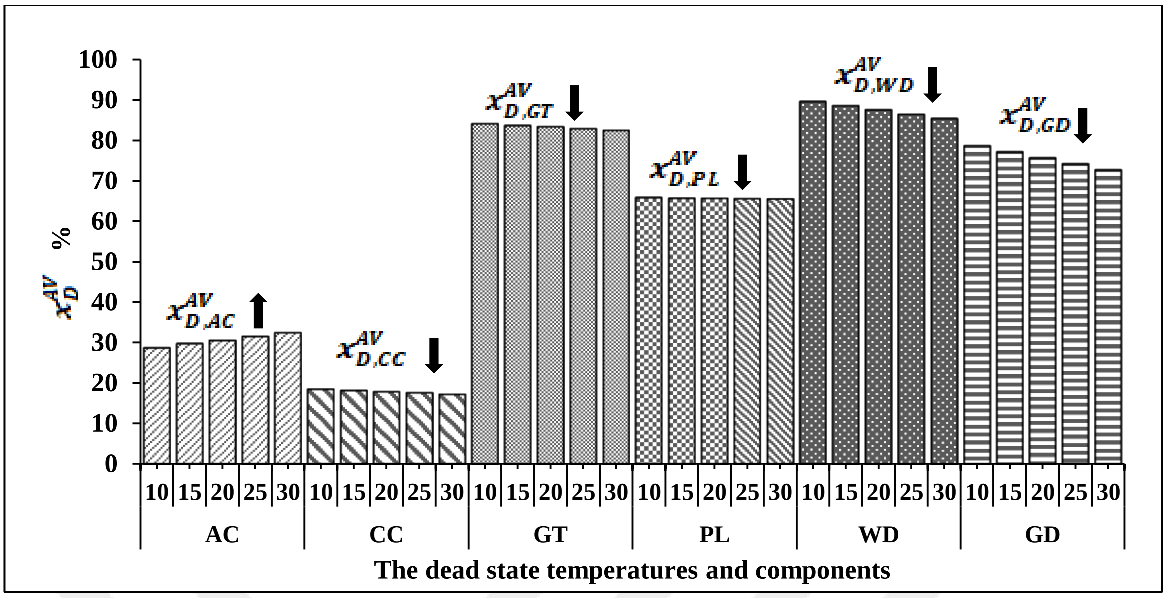


Figure 5.26. Effect of dead state temperatures on the ratio of avoidable exergy destruction value to exergy destruction value of components

- The avoidable exogenous exergy destruction "$\dot{E}x_D^{AV,EX}$" of any component indicates the part of the component being examined that can be reduced or recovered from exergy destruction by improving the efficiencies or reducing irreversibilities of the remaining components or the whole system. In this sense, CC (658.244 kW at 10°C) has the highest avoidable exogenous exergy destruction value, while PL (45.364% at 10°C) has the highest avoidable exogenous exergy destruction ratio (%). The other part of avoidable exergy destruction, avoidable endogenous exergy destruction "$\dot{E}x_D^{AV,EN}$", can be reduced by improving the efficiency of the component being examined. The main reason why WD (3414.047 kW at 30°C) and GD (4632.047 kW at 30°C) have the highest avoidable endogenous exergy destruction value and rate among the components is that their irreversibility in itself is very high. Furthermore, more than 81% of the avoidable endogenous exergy destruction of COGEN is due to these two components (WD and GD). Therefore, WD and GD have considerable technological and economic potential for improvement. The avoidable endogenous exergy destruction value of COGEN and all other components, except PL, is higher than avoidable exogenous exergy destruction value. In the calculation of the unavoidable endogenous exergy destruction "$\dot{E}x_D^{UN,EN}$" of *k*th component, the other components are considered to be in ideal working conditions (reversible), while the

kth component examined is considered to be in unavoidable conditions i.e. technological and economic limited. Therefore, the unavoidable endogenous exergy destruction value of all components with positive value cannot be prevent. To calculate the unavoidable exogenous exergy "$\dot{Ex}_D^{UN,EX}$" of kth component, the kth component is investigated under ideal conditions while the other components in the system are handled under unavoidable conditions. Therefore, the unavoidable exogenous exergy values of all components with positive values in the system cannot be reduced. In addition, since more than 82% of total unavoidable endogenous exergy destruction and more than 75% of total unavoidable exogenous exergy destruction is caused by CC, it can be seen that this component has a significant effect on unavoidable exergy destruction. The avoidable and unavoidable exergy destructions into endogenous and exogenous parts for the all components and COGEN are illustrated as Figure 5.27 and Figure 5.28. It is also used in Table 5.5 to better demonstrate the effect of dead state temperatures on combination of avoidable, unavoidable exergy destruction with endogenous, exogenous exergy destruction.

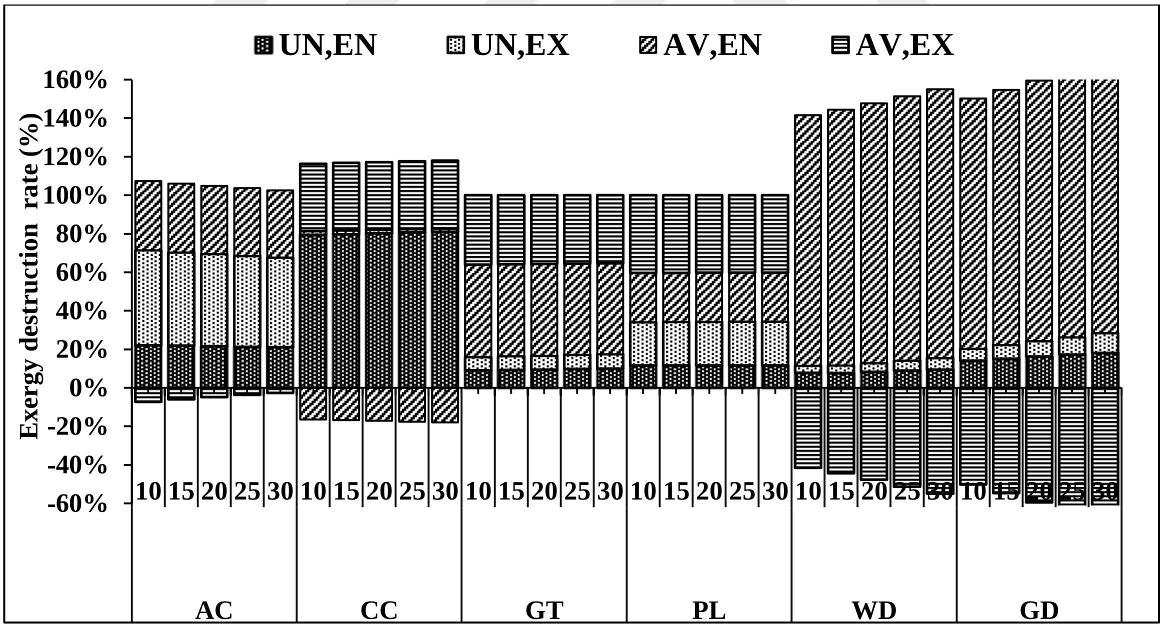


Figure 5.27. Effect of dead state temperatures on avoidable and unavoidable exergy destructions into endogenous and exogenous parts of components

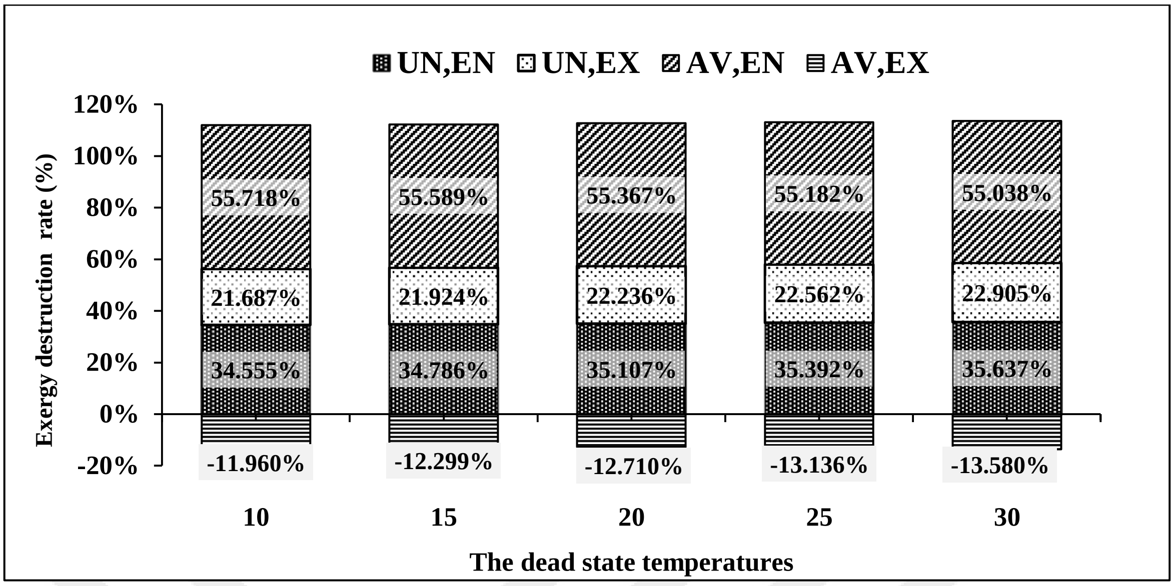


Figure 5.28. Effect of dead state temperatures on avoidable and unavoidable exergy destructions into endogenous and exogenous parts of COGEN

Table 5.5. Effect of dead state temperatures on combination of avoidable, unavoidable exergy destruction with endogenous, exogenous exergy destruction

Components	T(°C)	$\dot{Ex}_D^{UN,EN}$	$\dot{Ex}_D^{UN,EX}$	$\dot{Ex}_D^{AV,EN}$	$\dot{Ex}_D^{AV,EX}$
AC	10	22.156% ↓	49.210% ↓	35.923% ↓	-7.290% ↑
	15	21.855%	48.512%	35.696%	-6.063%
	20	21.582%	47.878%	35.401%	-4.861%
	25	21.299%	47.222%	35.187%	-3.708%
	30	21.025%	46.585%	34.979%	-2.589%
CC	10	51.427% ↑	30.164% ↑	11.652% ↓	6.757% ↓
	15	51.642%	30.326%	11.470%	6.562%
	20	51.842%	30.481%	11.301%	6.375%
	25	52.020%	30.626%	11.155%	6.199%
	30	52.181%	30.761%	11.027%	6.031%
GT	10	9.086% ↑	6.830% ↑	48.003% ↓	36.082% ↓
	15	9.346%	7.025%	47.743%	35.885%
	20	9.505%	7.145%	47.584%	35.766%
	25	9.755%	7.333%	47.334%	35.578%
	30	9.996%	7.514%	47.093%	35.398%
PL	10	11.664% ↓	22.514% ↑	25.571% ↓	40.251% ↓
	15	11.645%	22.613%	25.527%	40.215%
	20	11.624%	22.723%	25.483%	40.170%
	25	11.604%	22.827%	25.437%	40.131%
	30	11.584%	22.935%	25.391%	40.090%

Table 5.5. Effect of dead state temperatures on combination of avoidable, unavoidable exergy destruction with endogenous, exogenous exergy destruction (continued)

Components	T(°C)	$\dot{Ex}_{D}^{UN,EN}$	$\dot{Ex}_{D}^{UN,EX}$	$\dot{Ex}_{D}^{AV,EN}$	$\dot{Ex}_{D}^{AV,EX}$
WD	10	7.001%	3.422%	131.680%	-42.102%
	15	7.551% ↑	3.916% ↑	131.548% ↓	-43.015% ↓
	20	8.032%	4.428%	131.520%	-43.981%
	25	8.520%	5.041%	131.405%	-44.966%
	30	8.929%	5.690%	131.386%	-46.005%
GD	10	14.859%	6.461%	136.657%	-57.978%
	15	15.630% ↑	7.206% ↑	136.307% ↓	-59.144% ↓
	20	16.327%	8.015%	136.048%	-60.391%
	25	16.946%	8.902%	135.808%	-61.657%
	30	17.471%	9.877%	135.645%	-62.993%
COGEN	10	34.427%	21.627%	55.824%	-11.879%
	15	34.778% ↑	21.923% ↑	55.576% ↓	-12.276% ↓
	20	35.098%	22.235%	55.353%	-12.687%
	25	35.383%	22.561%	55.169%	-13.113%
	30	35.628%	22.904%	55.024%	-13.557%

- The negative impact of unavoidable exergy destruction on exergy efficiency can be seen with modified exergetic efficiency "ε_{mod}". In other words, the modified exergetic efficiency shows us the maximum exergy efficiency that can be achieved, considering that there are no technological and economic constraints on *k*th component. Thus, the effect of unavoidable conditions on exergy efficiency can be compared between components. The highest effect of unavoidable exergy destruction among components is CC, which has seen an increase in exergy efficiency of more than 32.5% at all dead state temperatures. The main reason for this is that more than 81% of the exergy destruction occurring in CC is unavoidable exergy destruction. On the other hand, the negative impact of unavoidable exergy destruction on exergy efficiency is seen in WD and GD, where exergy efficiency is decreased more than 20% at all dead state temperatures. The increase in modified exergy efficiency of COGEN, are directly proportional to the increase in dead state temperatures. Since more than 80% of total unavoidable exergy destruction of COGEN occurs at CC, the relationship of COGEN to dead state temperature can be said to be the same as CC. The effect of dead state temperatures on the modified exergy efficiency of components and COGEN as well as conventional exergy efficiency are given in Figure 5.29 and Figure 5.30, respectively.

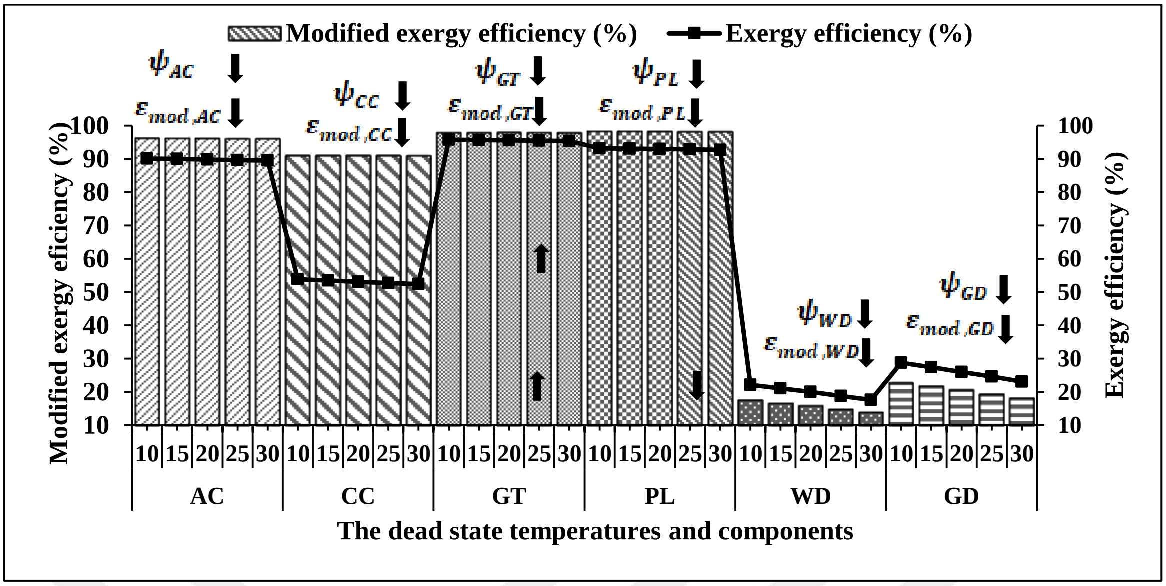


Figure 5.29. Effect of dead state temperatures on the modified exergy efficiency of components

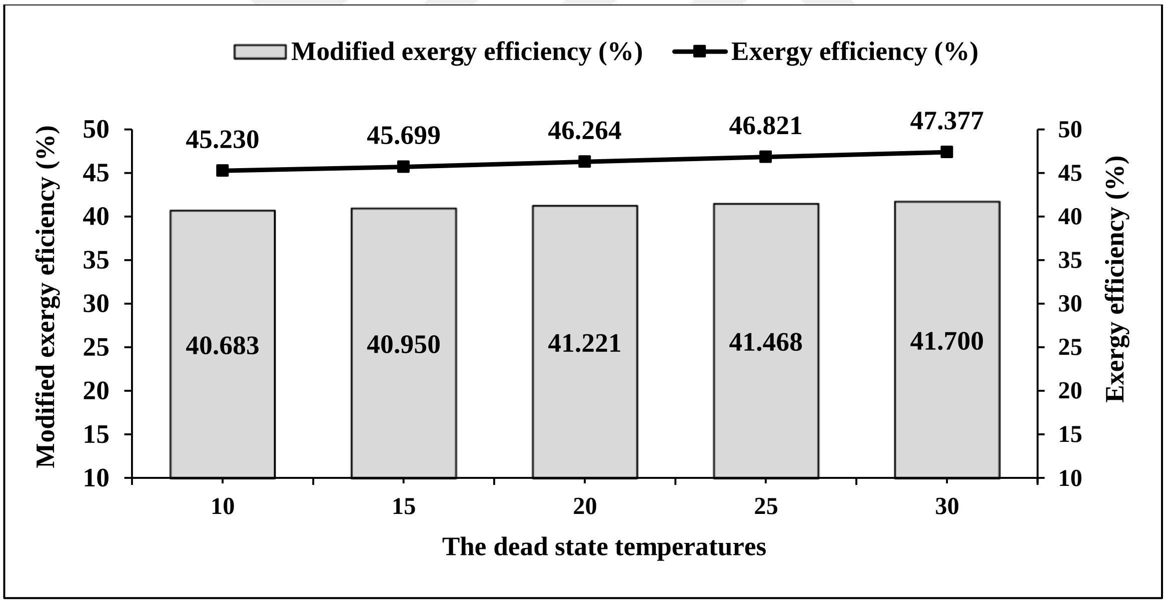


Figure 5.30. Effect of dead state temperatures on the modified exergy efficiency of COGEN

- The ratio of avoidable exergy destruction of *k*th to total fuel exergy supplied to the system (COGEN) "$y_{D,k}^{AV,EN}$" indicates the rank of avoidable exergy destruction potential among components. The highest "$y_{D,k}^{AV,EN}$" is found in WD and the lowest "$y_{D,k}^{AV,EN}$" is determined in PL, while the "$y_{D}^{AV,EN}$" can be ranked from high to low:

GD, WD, CC, GT, AC and PL. This ranking also shows the priority of technological and economic improvement among components. The increase in "$y_{D,k}^{AV,EN}$", which is directly proportional to the increase in dead state temperatures for all other components except CC and PL components, is shown in Figure 5.31.

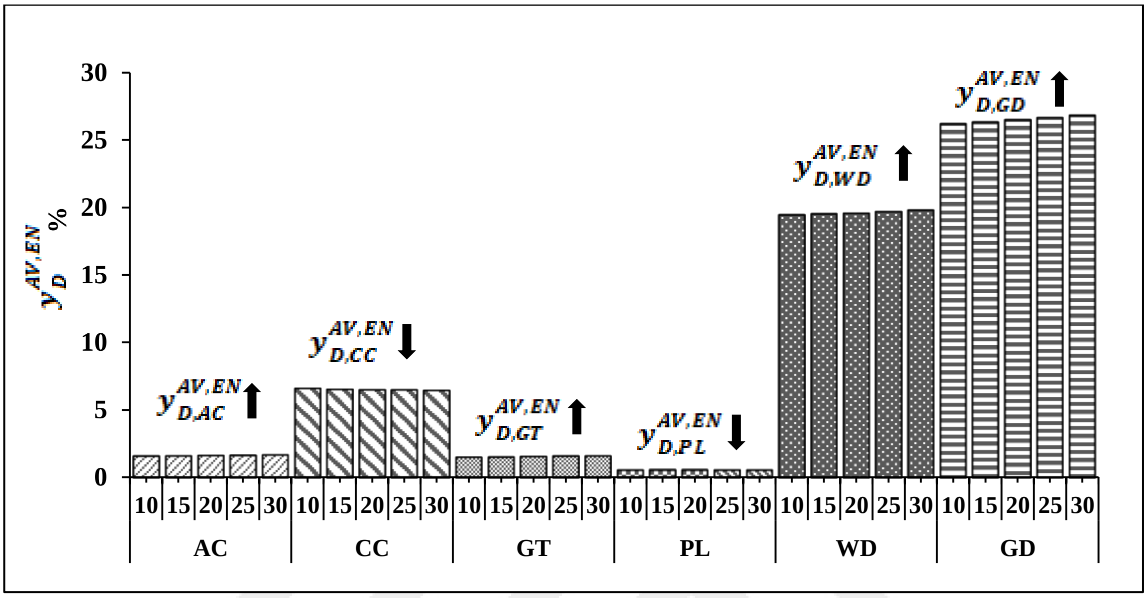


Figure 5.31. Effect of dead state temperatures on ratio of avoidable exergy destruction of *k*th to total fuel exergy supplied to COGEN

5.5. Evaluation of the System in terms of Advanced Exergoeconomic Analysis

In exergoeconomic analysis, which is carried out with the help of conventional exergy analysis, while determining the irreversibility costs of components in the system, the technological-economic constraints and the impact of components on each other cannot be determined exactly. Therefore, the costs of the destruction values obtained from the results of advanced exergy analysis are divided into endogenous-exogenous and avoidable-unavoidable parts and the results of advanced exergoeconomic analysis are obtained. In this study, exergy destruction costs and investment costs of components obtained by using SPECO method are first examined by dividing them into internal-external and avoidable-unavoidable parts. The other method is advanced EXCEM which is applied for the first time in the literature in this analysis the investment costs divided into internal-external and avoidable-unavoidable parts are combined with the results of advanced exergy analysis.

5.5.1. Advanced exergoeconomic analysis with SPECO method

The advanced exergoeconomic analysis is performed using unavoidable cost assumptions shown in Table 4.16 and equations shown in Table 3.3, and the results are shown in Table 5.6. According to these results, the following inferences can be made:

- The endogenous exergy destruction cost rates "$\dot{C}_D^{EN}$" of COGEN and its all components except PL and are determined to be higher than exogenous exergy destruction cost rates "$\dot{C}_D^{EX}$". According to this result, it is understood that the relationship between all components except PL is weak. This result shows that the PL is more affected than other system components, and that it is necessary to reduce the exergy destruction that occurs in other system components to reduce the exergy destruction cost rate that occur in these components. Although CC has the highest endogenous exergy destruction value, it is component GD that has the highest endogenous exergy destruction cost rate (226.555 $/h at 30 °C) at all dead state temperatures. The main reason for this is that the unit fuel exergy cost rate of CC is relatively lower than GD. The increase in endogenous exergy destruction rates of COGEN and its all components are observed to be directly proportional to the increase in dead state temperatures. In addition, the increase in exogenous exergy destruction rates of WD, GD and COGEN are determined to inversely proportional to the increase in dead state temperatures, whereas for other components this relationship is found to be inversely proportional. The endogenous and exogenous exergy destruction cost rates of all components and COGEN are shown as Figure 5.32 and Figure 5.33, respectively.

Table 5.6. Results of advanced exergy destruction cost rates for COGEN and its components ($/h)

Components	T (°C)	$\dot{C}_D$	$\dot{C}_D^{EN}$	$\dot{C}_D^{EX}$	$\dot{C}_D^{UN}$	$\dot{C}_D^{AV}$	$\dot{C}_D^{UN}$		$\dot{C}_D^{AV}$	
							$\dot{C}_D^{UN,EN}$	$\dot{C}_D^{UN,EX}$	$\dot{C}_D^{AV,EN}$	$\dot{C}_D^{AV,EX}$
AC	10	45.899	26.656	19.240	32.754	13.142	10.169	22.585	16.488	-3.346
	15	47.149	27.136	20.015	33.179	13.973	10.305	22.874	16.832	-2.859
	20	48.564	27.669	20.888	33.727	14.829	10.480	23.248	17.190	-2.360
	25	49.856	28.164	21.696	34.164	15.695	10.620	23.545	17.544	-1.849
	30	51.180	28.660	22.515	34.600	16.575	10.760	23.840	17.901	-1.325
CC	10	244.438	154.189	90.248	199.438	44.998	125.707	73.731	28.481	16.517
	15	246.424	155.521	90.901	201.987	44.435	127.256	74.731	28.264	16.170
	20	248.453	156.879	91.571	204.533	43.917	128.802	75.731	28.077	15.840
	25	250.418	158.204	92.216	206.962	43.457	130.269	76.693	27.934	15.523
	30	252.391	159.529	92.859	209.336	43.052	131.699	77.638	27.831	15.222
GT	10	29.771	16.994	12.773	4.738	25.029	2.705	2.033	14.289	10.740
	15	30.792	17.582	13.215	5.042	25.754	2.878	2.164	14.703	11.052
	20	31.804	18.159	13.650	5.297	26.513	3.023	2.273	15.136	11.377
	25	32.873	18.770	14.109	5.618	27.261	3.207	2.411	15.563	11.698
	30	33.960	19.391	14.576	5.947	28.020	3.395	2.552	15.996	12.024
PL	10	20.278	7.553	12.731	6.933	13.352	2.366	4.567	5.187	8.165
	15	20.344	7.560	12.779	6.968	13.372	2.369	4.599	5.192	8.179
	20	20.407	7.571	12.832	7.008	13.395	2.372	4.636	5.199	8.195
	25	20.453	7.577	12.877	7.043	13.411	2.374	4.669	5.203	8.208
	30	20.496	7.580	12.921	7.077	13.425	2.375	4.702	5.205	8.219
WD	10	110.939	153.843	-42.910	11.562	99.371	7.766	3.796	146.077	-46.706
	15	113.602	158.014	-44.416	13.026	100.572	8.578	4.448	149.436	-48.864
	20	116.720	162.886	-46.166	14.544	102.176	9.375	5.169	153.511	-51.335
	25	119.994	167.903	-47.908	16.272	103.723	10.224	6.048	157.680	-53.957
	30	123.617	173.445	-49.833	18.071	105.541	11.037	7.033	162.408	-56.867
GD	10	135.584	205.439	-69.850	28.909	106.680	20.148	8.761	185.291	-78.611
	15	138.372	210.241	-71.868	31.599	106.774	21.628	9.971	188.612	-81.839
	20	141.621	215.794	-74.174	34.474	107.146	23.123	11.351	192.671	-85.525
	25	144.719	221.060	-76.344	37.407	107.309	24.524	12.883	196.536	-89.227
	30	147.959	226.555	-78.592	40.465	107.499	25.850	14.615	200.705	-93.206
COGEN	10	478.263	564.674	22.232	284.334	302.572	168.861	115.473	395.813	-93.241
	15	483.038	576.054	20.626	291.801	304.880	173.014	118.787	403.039	-98.161
	20	487.851	588.958	18.601	299.583	307.976	177.175	122.408	411.784	-103.808
	25	492.636	601.678	16.646	307.466	310.856	181.218	126.249	420.460	-109.604
	30	497.363	615.160	14.446	315.496	314.112	185.116	130.380	430.046	-115.933

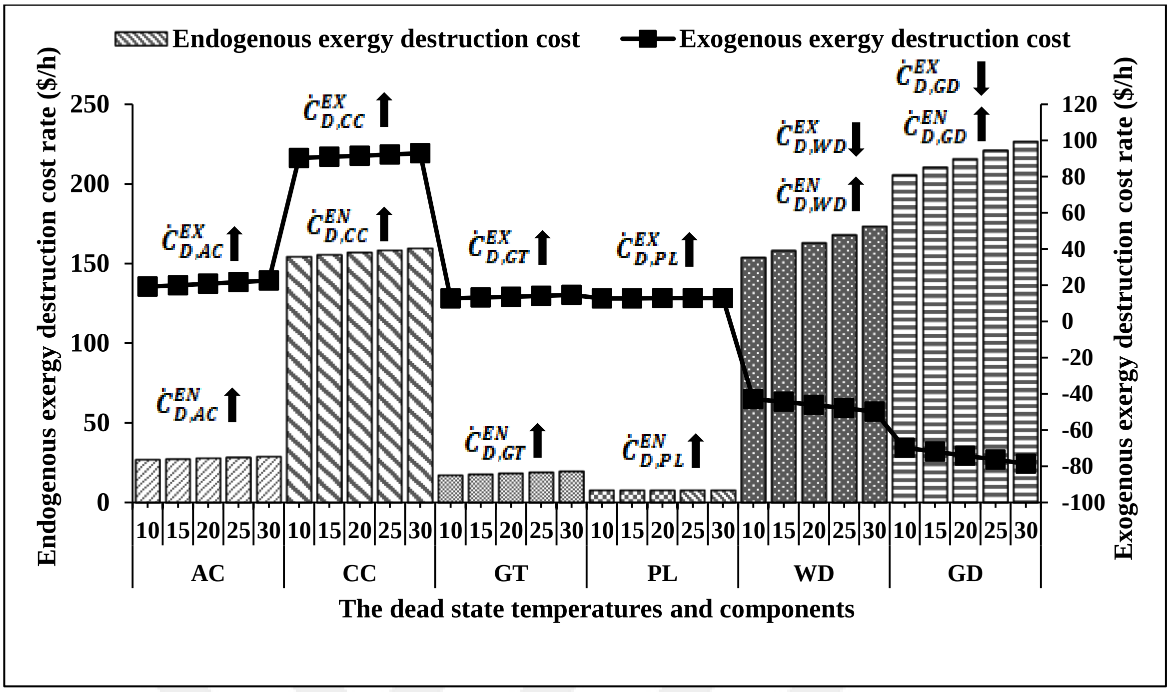


Figure 5.32. Effect of dead state temperatures on endogenous and exogenous exergy destruction cost rates of components

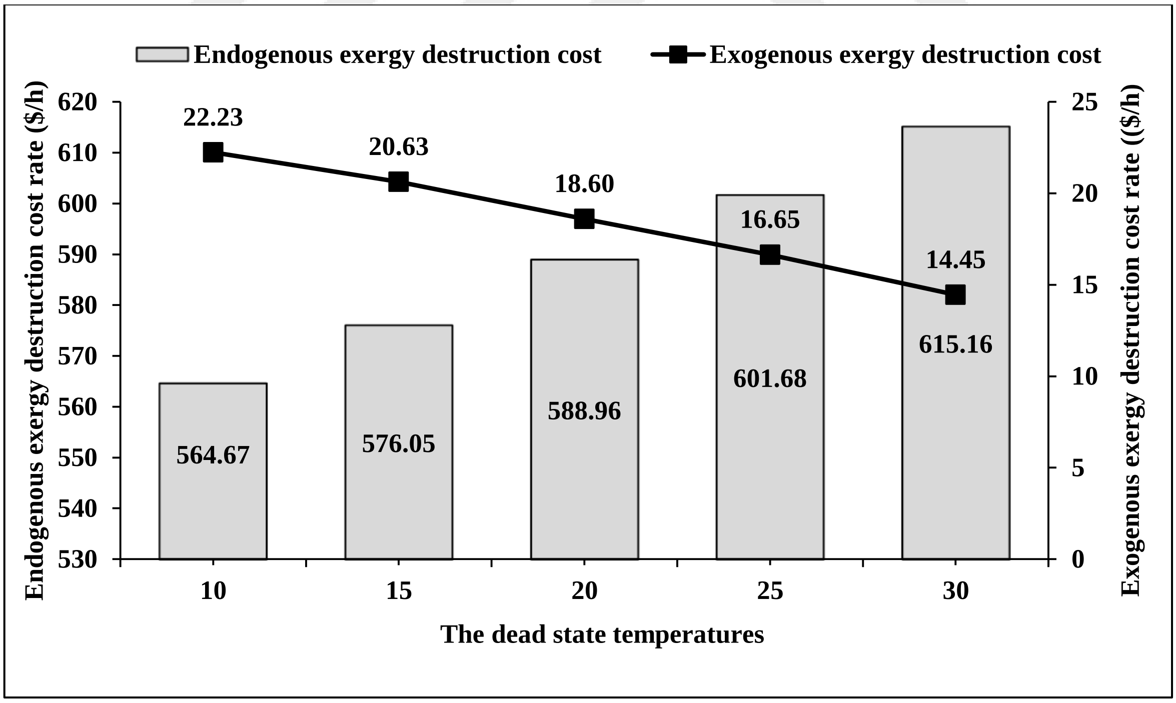


Figure 5.33. Effect of dead state temperatures on endogenous and exogenous exergy destruction cost rates of COGEN

- As shown in Table 5.6, it is determined that the avoidable exergy destruction cost rate “$\dot{C}_D^{UN}$” of COGEN and its all components except AC and CC, is higher than the unavoidable exergy destruction cost rate. In this case, it can be determined that these components (COGEN and its components except AC and CC) mentioned have lower improvement potential. CC, which has the highest unavoidable exergy destruction cost rate (209.336 $/h at 30 °C), accounts for more than 80% of the unavoidable exergy destruction cost rate of COGEN at all dead state temperatures. In addition to this interpretation, although CC has the highest exergy destruction cost rate, the component with the highest improvement potential is GD (107.499 $/h at 30 °C), which has the highest avoidable exergy destruction cost rate “$\dot{C}_D^{AV}$” at all dead state temperatures. When the relation of the avoidable and unavoidable exergy destruction rates of the components with temperature is examined, it can be determined that the increase in avoidable exergy destruction cost rate of COGEN and its all components except CC is directly proportional to the increase in dead state temperatures, while the increase in unavoidable exergy destruction cost rate of COGEN and its all components is directly proportional to the increase in dead state temperatures. These relationships are illustrated in Figure 5.34 and Figure 5.35 for all components and COGEN, respectively.

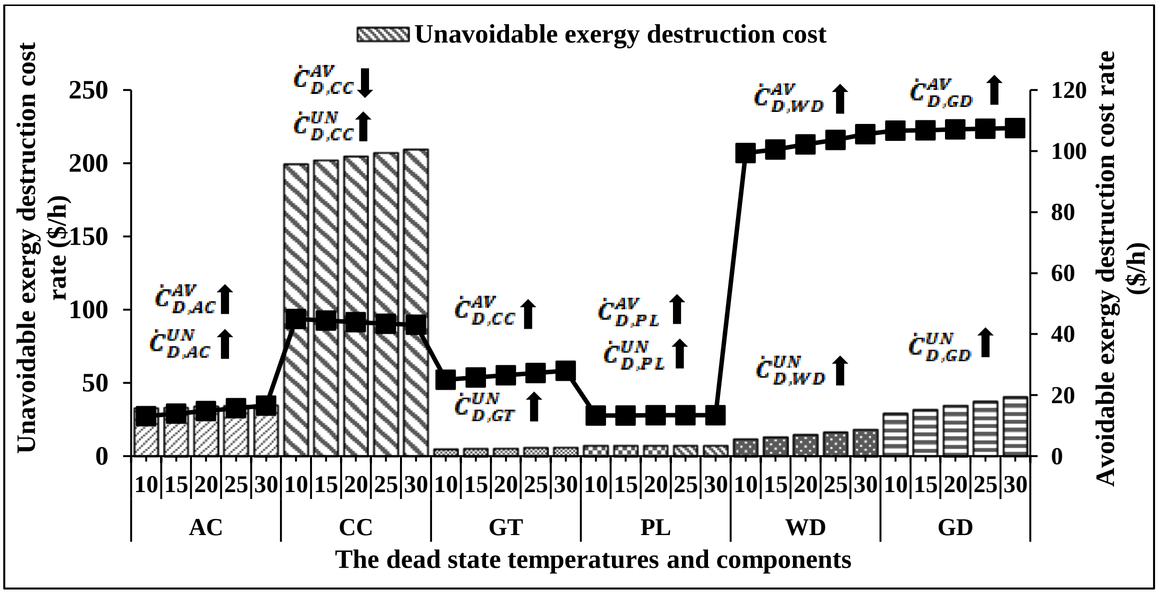


Figure 5.34. Effect of dead state temperatures on unavoidable and avoidable exergy destruction cost rates of components

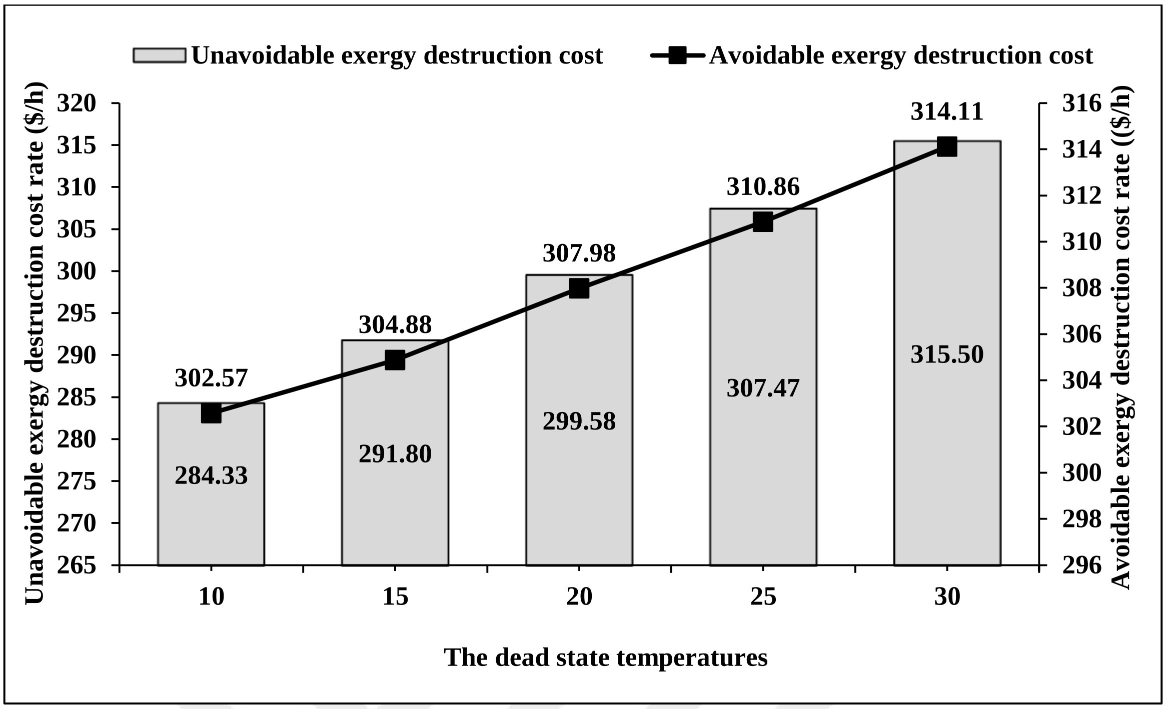


Figure 5.35. Effect of dead state temperatures on unavoidable and avoidable exergy destruction cost rates of COGEN

- The avoidable endogenous exergy destruction cost rate "$\dot{C}_D^{AV,EN}$" and the avoidable exogenous exergy destruction cost rate "$\dot{C}_D^{AV,EX}$" are endogenous and exogenous parts of the avoidable exergy destruction cost rate "$\dot{C}_D^{AV}$", respectively. It is found that the endogenous parts of COGEN and its components except PL are higher than the exogenous parts. Therefore, it can be explained that a large part of the avoidable exergy destruction cost rate of components expect PL is due to the irreversibilities of the components themselves. This means that the avoidable endogenous exergy destruction cost rate of these components can be reduced by reducing the avoidable endogenous exergy destruction value of the components whose efficiency is been improved.

  The unavoidable endogenous exergy destruction cost rate "$\dot{C}_D^{UN,EN}$" of any *k*th component defines the part that cannot be reduced due to the irreversibility of the *k*th component being examined, while unavoidable exogenous exergy destruction cost rate "$\dot{C}_D^{UN,EX}$" refers to the part that cannot be reduced due to the irreversibility of other components in the system. When the overall system is examined, it is determined that the endogenic parts of the other components, except AC and PL, are higher than the exogenous parts. Furthermore, more than 71% of the total unavoidable endogenous exergy destruction cost rate is due to irreversibilities occurring in CC, and more than 59% of unavoidable exogenous exergy destruction cost rate is due to the negative effect on CC of irreversibilities in other components at all dead state temperatures. The avoidable and unavoidable exergy destructions cost rate into endogenous and exogenous parts for the all components and COGEN are illustrated as Figure 5.36 and Figure 5.37. It is also used in Table 5.7 to better demonstrate the effect of dead state temperatures on combination of avoidable, unavoidable exergy destruction cost rate with endogenous, exogenous exergy destruction.

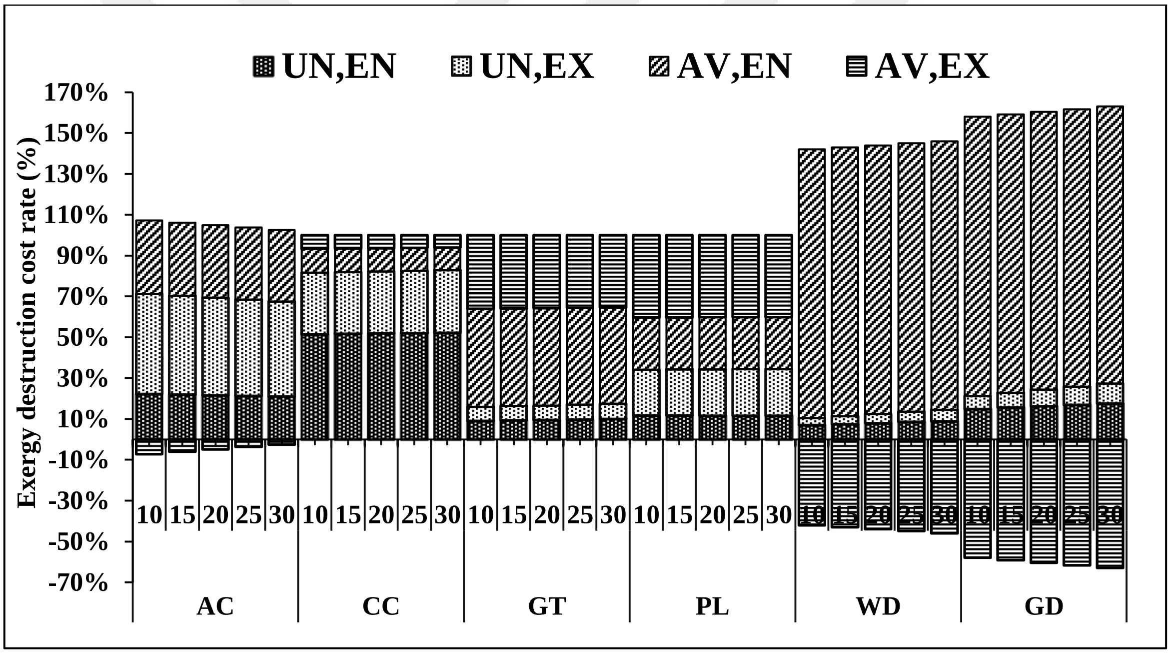


Figure 5.36. Effect of dead state temperatures on avoidable and unavoidable exergy destructions cost rate into endogenous and exogenous parts of components

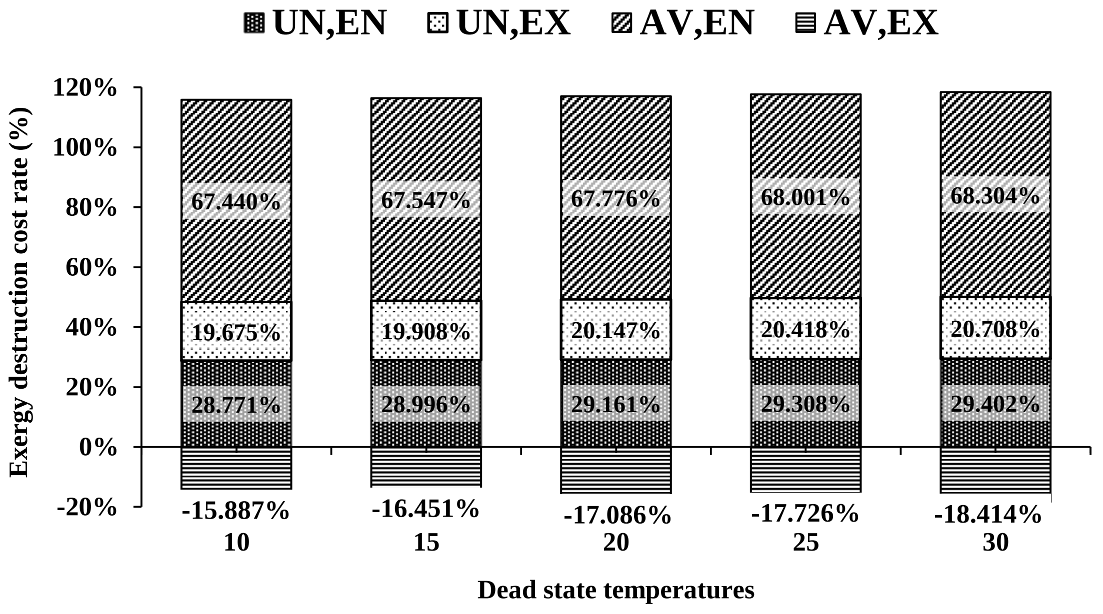


Figure 5.37. Effect of dead state temperatures on avoidable and unavoidable exergy destructions into endogenous and exogenous parts of COGEN

Table 5.7. Effect of dead state temperatures on combination of avoidable and unavoidable exergy destruction with endogenous and exogenous exergy destruction (%)

Components	T(°C)	$\dot{Ex}_D^{UN.EN}$	$\dot{Ex}_D^{UN.EX}$	$\dot{Ex}_D^{AV.EN}$	$\dot{Ex}_D^{AV.EX}$
AC	10	22.155% ↓	49.206% ↓	35.922% ↓	-7.290% ↑
	15	21.856%	48.514%	35.700%	-6.064%
	20	21.580%	47.871%	35.397%	-4.860%
	25	21.301%	47.226%	35.189%	-3.709%
	30	21.024%	46.581%	34.977%	-2.589%
CC	10	51.427% ↑	30.163% ↑	11.652% ↓	6.757% ↓
	15	51.641%	30.326%	11.470%	6.562%
	20	51.842%	30.481%	11.301%	6.375%
	25	52.021%	30.626%	11.155%	6.199%
	30	52.181%	30.761%	11.027%	6.031%
GT	10	9.086% ↑	6.829% ↑	47.996% ↓	36.075% ↓
	15	9.347%	7.028%	47.749%	35.892%
	20	9.505%	7.147%	47.591%	35.772%
	25	9.756%	7.334%	47.343%	35.585%
	30	9.997%	7.515%	47.102%	35.406%

Table 5.7. Effect of dead state temperatures on combination of avoidable and unavoidable exergy destruction with endogenous and exogenous exergy destruction (%) (continued)

Components	***T*(°C)**	$\dot{Ex}_D^{UN.EN}$	$\dot{Ex}_D^{UN.EX}$	$\dot{Ex}_D^{AV.EN}$	$\dot{Ex}_D^{AV.EX}$
PL	10	11.668% ↓	22.522% ↑	25.579% ↓	40.265% ↓
	15	11.645%	22.606%	25.521%	40.203%
	20	11.623%	22.718%	25.477%	40.158%
	25	11.607%	22.828%	25.439%	40.131%
	30	11.588%	22.941%	25.395%	40.101%
WD	10	7.000% ↑	3.422% ↑	131.673% ↓	-42.101% ↓
	15	7.551%	3.915%	131.543%	-43.013%
	20	8.032%	4.429%	131.521%	-43.981%
	25	8.520%	5.040%	131.407%	-44.966%
	30	8.928%	5.689%	131.380%	-46.003%
GD	10	14.860% ↑	6.462% ↑	136.661% ↓	-57.980% ↓
	15	15.630%	7.206%	136.308%	-59.144%
	20	16.327%	8.015%	136.047%	-60.390%
	25	16.946%	8.902%	135.805%	-61.655%
	30	17.471%	9.878%	135.649%	-62.994%
COGEN	10	28.771% ↑	19.675% ↑	67.440% ↑	-15.887% ↓
	15	28.996%	19.908%	67.547%	-16.451%
	20	29.161%	20.147%	67.776%	-17.086%
	25	29.308%	20.418%	68.001%	-17.726%
	30	29.402%	20.708%	68.304%	-18.414%

Table 5.8 shows the investment cost rates divided into parts obtained by using advanced exergy analysis of COGEN and its components. According to these results;

- The endogenous investment cost rates “$\dot{Z}_k^{EN}$” of COGEN and its all components except AC and PL are found to be higher than the exogenous investment cost rate “$\dot{Z}_k^{EX}$” at all dead state temperatures. Therefore, it can be said that the interaction between components has a higher impact on the investment cost of AC and PL than other components and COGEN. In other words, AC and PL are affected by their thermodynamic inefficiencies resulting from their own operating conditions, while they are less affected by the operating conditions or structural features of the other COGEN components. While the increase in the endogenous investment cost rates of AC is found to be directly proportional to the increase in dead state temperatures, this relationship is found to be inversely proportional to CC, PL and COGEN. Furthermore, while the increase in the exogenous investment cost rates of AC is inversely proportional to the increase in dead state temperatures, this relationship is directly proportional for CC, PL and COGEN. It is also seen that the dead state temperatures have no effect on GT, WD and GD. These relationships are illustrated in Figure 5.38 and Figure 5.39 for all components and COGEN, respectively.

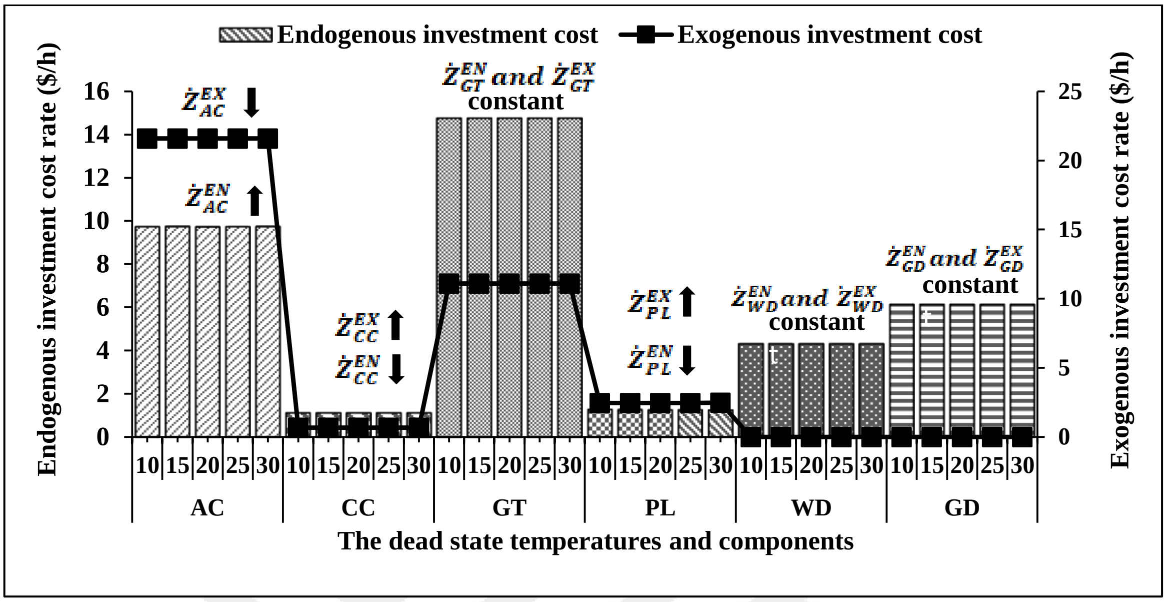


Figure 5.38. Effect of dead state temperatures on endogenous and exogenous investment cost rates of components

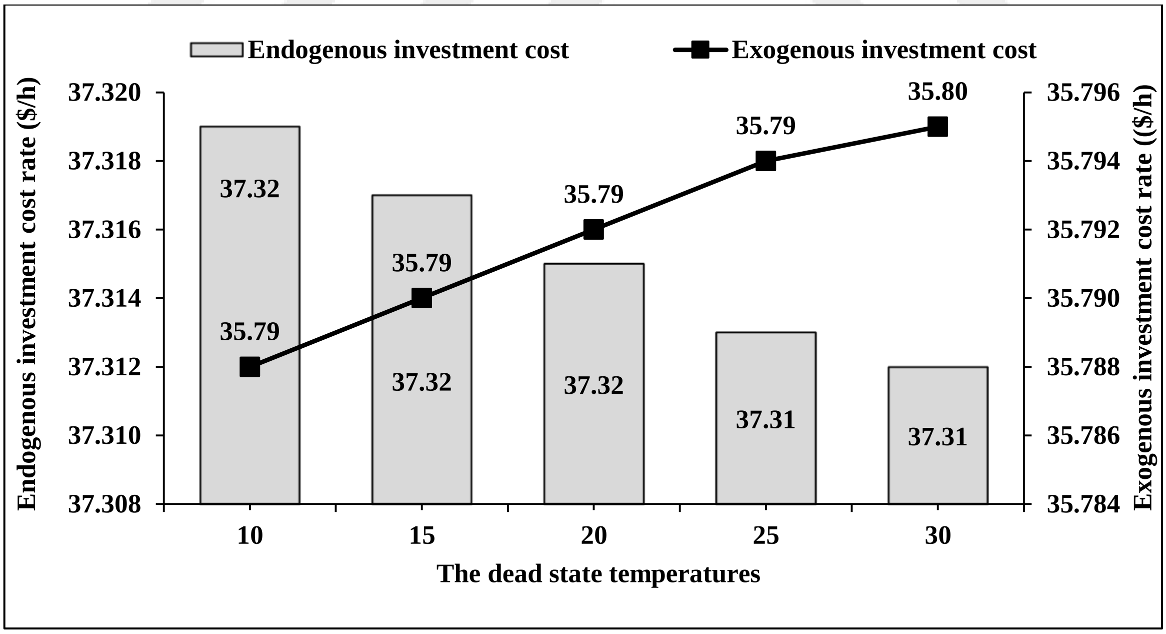


Figure 5.39. Effect of dead state temperatures on endogenous and exogenous investment cost rates of COGEN

Table 5.8. Results of advanced investment cost rates ($/h) and the modified

Components	T (°C)	$\dot{Z}$	$\dot{Z}^{EN}$	$\dot{Z}^{EX}$	$\dot{Z}^{UN}$	$\dot{Z}^{AV}$	$\dot{Z}^{UN}$		$\dot{Z}^{AV}$		$\dot{f}^{AV.EN}$
							$\dot{Z}^{UN,EN}$	$\dot{Z}^{UN,EX}$	$\dot{Z}^{AV,EN}$	$\dot{Z}^{AV,EX}$	
AC	10	31.324	9.725	21.599	30.995	0.329	9.623	21.372	0.102	0.227	0.615%
	15		9.729	21.595	30.949	0.375	9.612	21.337	0.117	0.258	0.690%
	20		9.733	21.591	30.903	0.421	9.602	21.301	0.131	0.290	0.756%
	25		9.737	21.587	30.857	0.467	9.592	21.265	0.145	0.322	0.820%
	30		9.741	21.583	30.812	0.512	9.582	21.230	0.159	0.353	0.880%
CC	10	1.780	1.122	0.658	1.466	0.314	0.924	0.542	0.198	0.116	0.690%
	15		1.121	0.659	1.468	0.312	0.925	0.543	0.196	0.116	0.691%
	20		1.121	0.659	1.469	0.311	0.925	0.544	0.196	0.115	0.692%
	25		1.120	0.660	1.471	0.309	0.926	0.545	0.194	0.115	0.692%
	30		1.120	0.660	1.472	0.308	0.926	0.546	0.194	0.114	0.692%
GT	10	25.835	14.749	11.086	18.537	7.298	10.583	7.954	4.166	3.132	22.574%
	15		14.749	11.086	18.537	7.298	10.583	7.954	4.166	3.132	22.079%
	20		14.749	11.086	18.537	7.298	10.583	7.954	4.166	3.132	21.583%
	25		14.749	11.086	18.537	7.298	10.583	7.954	4.166	3.132	21.116%
	30		14.749	11.086	18.537	7.298	10.583	7.954	4.166	3.132	20.663%
PL	10	3.712	1.267	2.445	3.659	0.053	1.249	2.410	0.018	0.035	0.346%
	15		1.262	2.450	3.667	0.045	1.247	2.420	0.015	0.030	0.288%
	20		1.256	2.456	3.677	0.035	1.244	2.433	0.012	0.023	0.230%
	25		1.251	2.461	3.687	0.025	1.242	2.445	0.009	0.016	0.173%
	30		1.246	2.466	3.696	0.016	1.240	2.456	0.006	0.010	0.115%
WD	10	4.313	4.313	0.000	2.028	2.285	2.028	0.000	2.285	0.000	1.540%
	15		4.313	0.000	1.988	2.325	1.988	0.000	2.325	0.000	1.532%
	20		4.313	0.000	1.946	2.367	1.946	0.000	2.367	0.000	1.518%
	25		4.313	0.000	1.897	2.416	1.897	0.000	2.416	0.000	1.509%
	30		4.313	0.000	1.844	2.469	1.844	0.000	2.469	0.000	1.497%
GD	10	6.143	6.143	0.000	2.997	3.146	2.997	0.000	3.146	0.000	1.670%
	15		6.143	0.000	2.943	3.200	2.943	0.000	3.200	0.000	1.668%
	20		6.143	0.000	2.884	3.259	2.884	0.000	3.259	0.000	1.663%
	25		6.143	0.000	2.819	3.324	2.819	0.000	3.324	0.000	1.663%
	30		6.143	0.000	2.747	3.396	2.747	0.000	3.396	0.000	1.664%
COGEN	10	73.107	37.319	35.788	59.682	13.425	27.404	32.278	9.915	3.510	-
	15		37.317	35.790	59.552	13.555	27.298	32.254	10.019	3.536	-
	20		37.315	35.792	59.416	13.691	27.184	32.232	10.131	3.560	-
	25		37.313	35.794	59.268	13.839	27.059	32.209	10.254	3.585	-
	30		37.312	35.795	59.108	13.999	26.922	32.186	10.390	3.609	-

- The unavoidable investment cost rates "$\dot{Z}^{UN}$" of COGEN and its all components except WD and GD are found to be higher than the avoidable investment cost rates "$\dot{Z}^{AV}$" at all dead state temperatures. For this reason, improvement potential of investment cost of WD and GD is higher than other components, as well as the improvement potential of investment cost of the COGEN (whole system) is low. More than 51% of the unavoidable investment cost rate of COGEN occurs in AC, while more than 52% of the avoidable investment cost rate occurs in GT. Therefore, in order to improve the investment cost rate of COGEN, there needs to be more focus on the investment cost rate of GT. While the increase in the unavoidable investment cost rates of CC and PL is found to be directly proportional to the increase in dead state temperatures, this relation is found to be inversely proportional to AC, WD, GD and COGEN. Furthermore, while the increase in the avoidable investment cost rate of AC, WD, GD and COGEN is found to be directly proportional to the increase in dead state temperatures, this relationship is inversely proportional for CC and PL. it is also seen that temperature has no effect on GT. These relationships are shown in Figure 5.40 and Figure 5.41 for all components and COGEN, respectively.

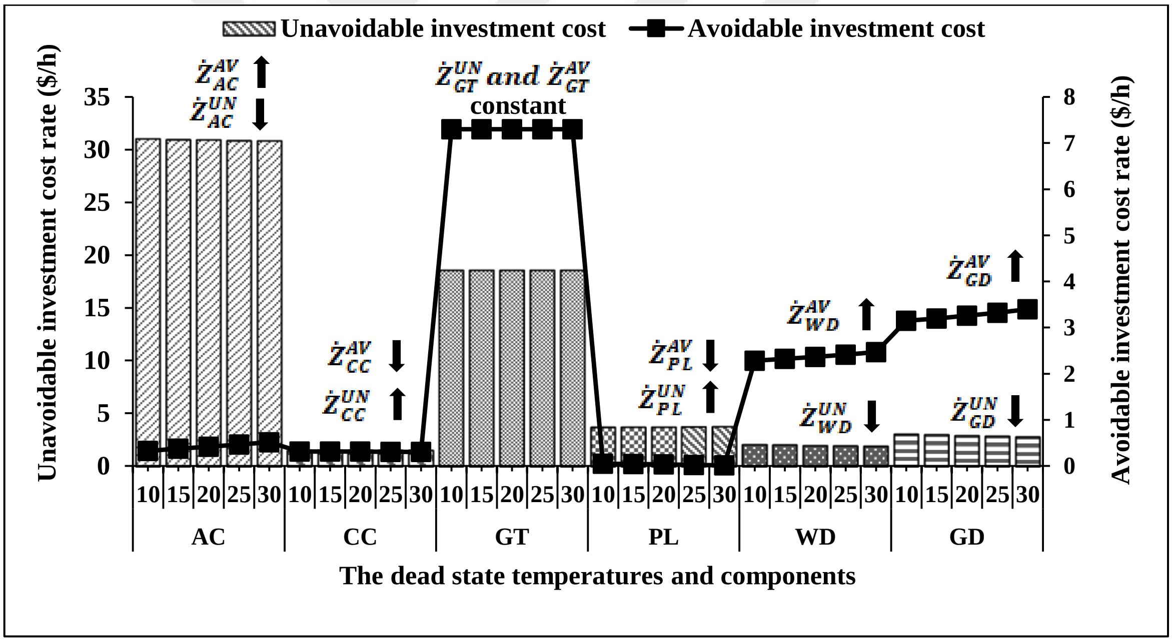


Figure 5.40. Effect of dead state temperatures on unavoidable and avoidable investment cost rates of components

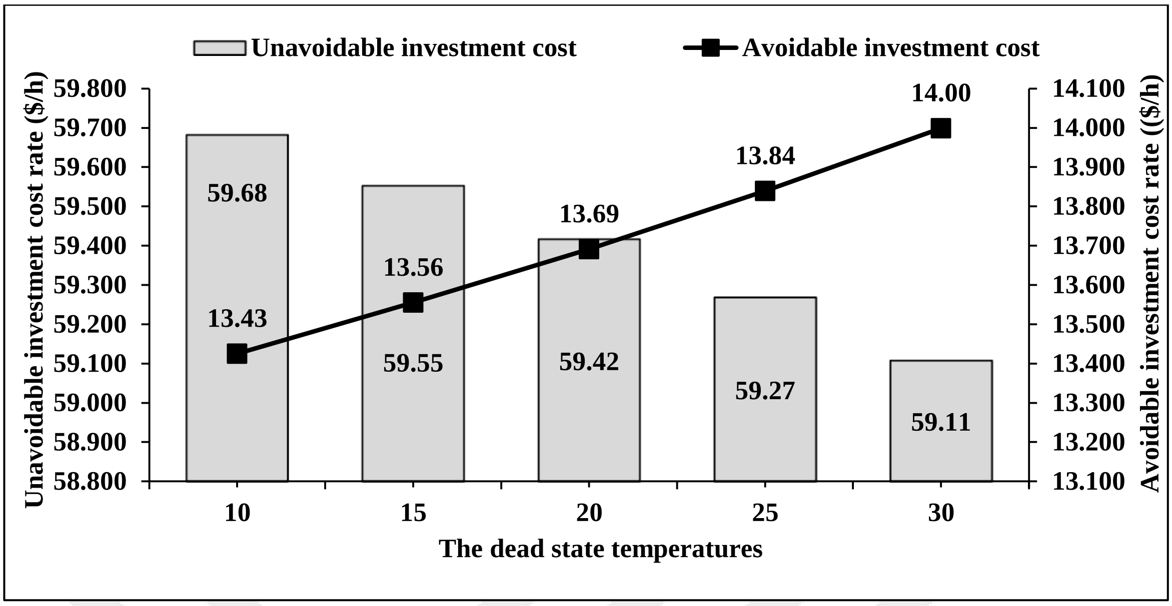


Figure 5.41. Effect of dead state temperatures on unavoidable and avoidable investment cost rates of COGEN

- The unavoidable endogenous investment cost rates "$\dot{Z}^{UN,EN}$" of CC, GT, WD and GD are higher than its exogenous part of unavoidable investment cost rates at all dead state temperatures. Therefore, a large part of the unavoidable investment cost rate of these components is due to the irreversibility of that component. In addition, the unavoidable endogenous investment cost rates "$\dot{Z}^{UN,EX}$" of AC, PL and COGEN (whole system) are higher than their endogenous part of unavoidable investment cost rates. For these components, a large part of the unavoidable investment cost rate can be said to be due to the irreversibility of other components.

  The avoidable endogenous investment cost rates "$\dot{Z}^{AV,EN}$" of COGEN and its components except AC and PL are higher than their unavoidable investment cost rates "$\dot{Z}^{AV,EX}$" at all dead state temperatures. The effective way to improve the avoidable investment cost of AC and PL is by reducing the irreversibility and inefficiencies that occur in other components. For other components such as CC, GT, WD and GD, this method can be achieved by reducing the irreversibility that occur within them. In other words, this can be done by replacing the material in which the component is made, or by using less costly manufacturing methods, if the working conditions permit. The avoidable and unavoidable investment cost rate into endogenous and exogenous parts for the all components and COGEN are illustrated as Figure 5.42 and Figure 5.43. It is also used in Table 5.9 to better demonstrate the effect of dead state temperatures on combination of avoidable, unavoidable investment cost rate with endogenous, exogenous investment cost rate.

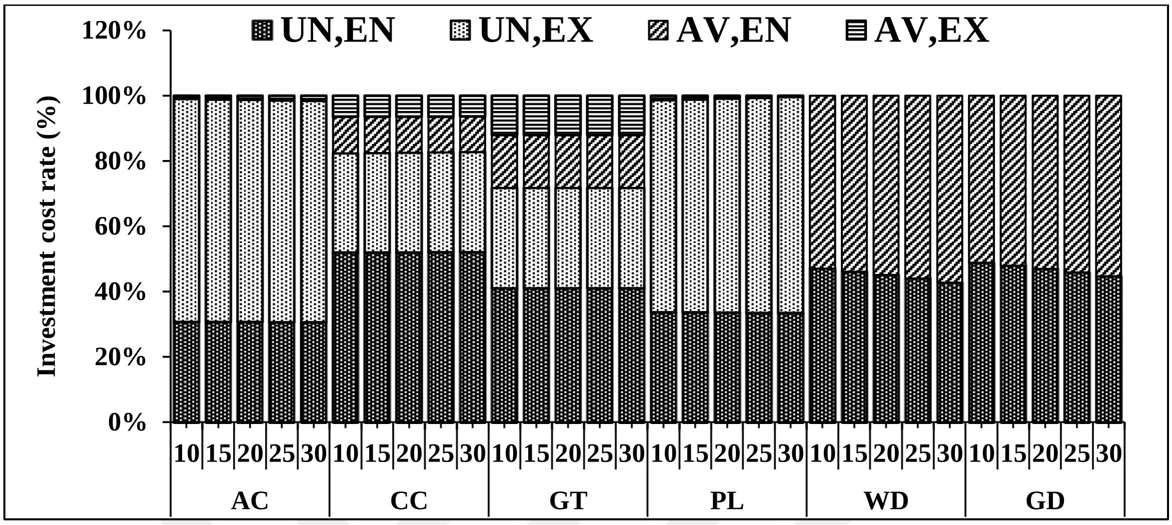


Figure 5.42. Effect of dead state temperatures on avoidable and unavoidable investment cost rate into endogenous and exogenous parts of components

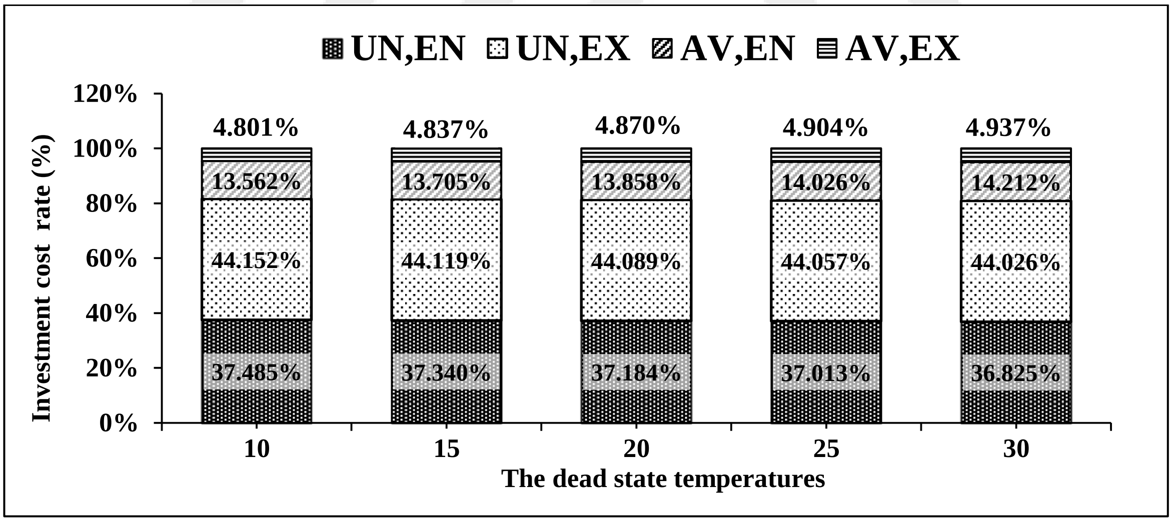


Figure 5.43. Effect of dead state temperatures on avoidable and unavoidable investment cost rate into endogenous and exogenous parts of COGEN

Table 5.9. Effect of dead state temperatures on combination of avoidable and unavoidable investment cost rate with endogenous and exogenous investment cost rate (%)

Components	T(°C)	$\dot{Z}^{UN,EN}$	$\dot{Z}^{UN,EX}$	$\dot{Z}^{AV,EN}$	$\dot{Z}^{AV,EX}$
AC	10	30.721%	68.229%	0.326%	0.725%
	15	30.686%	68.117%	0.374%	0.824%
	20	30.654% ↓	68.002% ↓	0.418% ↑	0.926% ↑
	25	30.622%	67.887%	0.463%	1.028%
	30	30.590%	67.776%	0.508%	1.127%
CC	10	51.910%	30.449%	11.124%	6.517%
	15	51.966%	30.506%	11.011%	6.517%
	20	51.966% ↑	30.562% ↑	11.011% ↓	6.461% ↓
	25	52.022%	30.618%	10.899%	6.461%
	30	52.022%	30.674%	10.899%	6.404%
GT	10	40.964%	30.788%	16.125%	12.123%
	15	40.964%	30.788%	16.125%	12.123%
	20	40.964% ↕	30.788% ↕	16.125% ↕	12.123% ↕
	25	40.964%	30.788%	16.125%	12.123%
	30	40.964%	30.788%	16.125%	12.123%
PL	10	33.648%	64.925%	0.485%	0.943%
	15	33.594%	65.194%	0.404%	0.808%
	20	33.513% ↓	65.544% ↑	0.323% ↓	0.620% ↓
	25	33.459%	65.867%	0.242%	0.431%
	30	33.405%	66.164%	0.162%	0.269%
WD	10	47.021%	0.000%	52.979%	0.000%
	15	46.093%	0.000%	53.907%	0.000%
	20	45.119% ↓	0.000% ↕	54.881% ↑	0.000% ↕
	25	43.983%	0.000%	56.017%	0.000%
	30	42.754%	0.000%	57.246%	0.000%
GD	10	48.787%	0.000%	51.213%	0.000%
	15	47.908%	0.000%	52.092%	0.000%
	20	46.948% ↓	0.000% ↕	53.052% ↑	0.000% ↕
	25	45.890%	0.000%	54.110%	0.000%
	30	44.718%	0.000%	55.282%	0.000%
COGEN	10	37.485%	44.152%	13.562%	4.801%
	15	37.340%	44.119%	13.705%	4.837%
	20	37.184% ↓	44.089% ↓	13.858% ↑	4.870% ↑
	25	37.013%	44.057%	14.026%	4.904%
	30	36.825%	44.026%	14.212%	4.937%

- The modified exergoeconomic factor “$\dot{f}^{AV.EN}$” is used to determine the contribution of avoidable endogenous investment cost rate “$\dot{Z}^{AV.EN}$” to total avoidable endogenous cost rate “$\dot{Z}^{AV,EN}+\dot{C}_D^{AV,EN}$”. Although GT (%22.574 at 10°C) has the highest modified exergoeconomic factor among the components in the system, it is seen that the avoidable endogenous cost rate is relatively low to the avoidable endogenous exergy destruction cost rate. It can also be determined that the component with the lowest modified exergoeconomic factor is PL (%0.115 at 30°C), and that the effect of exergy destruction cost rate on total cost rate among components is highest. Since all components have a very low advanced exergoeconomic factor, it has been determined that the reduction of irreversibilities within the components can be more economically effective. In addition, as shown in Figure 5.44 for this system, the increase in modified exergoeconomic factors of AC and CC is directly proportional to the increase in dead state temperatures, while this relationship is found to be inversely proportional for the other components.

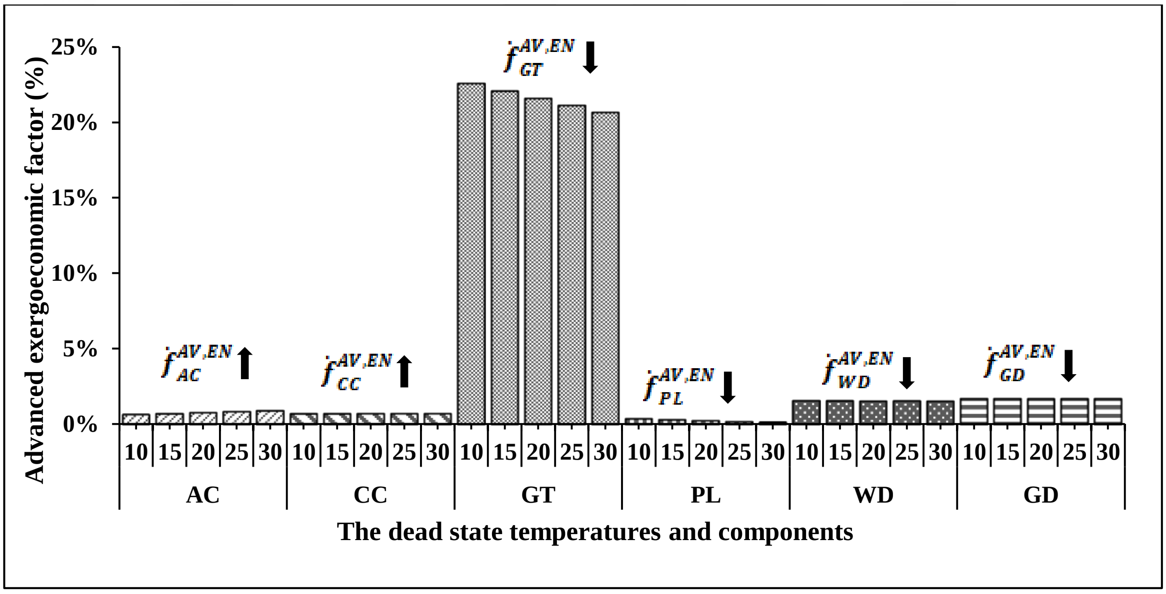


Figure 5.44. Effect of dead state temperatures on modified exergoeconomic factor of components

5.5.2. Advanced exergoeconomic analysis with EXCEM method

The advanced EXCEM method, which creates a new approach to the EXCEM method based on advanced exergy analysis, is used in this study for the first time in the literature. In other words, exergetic cost parameters “$\dot{R}_{ex,D}$” based on exergy destruction obtained from EXCEM analysis are divided into endogenic-exogenous and avoidable-unavoidable parts. The following inferences can be made based on the results of advanced exergetic cost parameters shown in Table 5.10:

- The endogenous exergetic cost parameters “$\dot{R}^{EN}_{ex,D}$” of COGEN and its components except PL are higher than their exogenous exergetic cost parameters “$\dot{R}^{EX}_{ex,D}$” at all dead state temperatures. In this case, it is determined that the irreversibilities within the other components except PL have more negative impact in terms of the investment cost. It is once again understandable that CC (12.8584 GJ/$ at 30°C) with the highest exergetic cost parameter should be focused on. Furthermore, the negative effect of irreversibilities on PL occurring in other components is higher than that of its own irreversibilities. Therefore, the exogenous exergy destruction value per unit investment cost rate is higher for PL. The increase in endogenous exergetic cost parameters of COGEN and its component except PL is found to be directly proportional to the increase dead state temperatures, while for PL this relationship is inversely proportional. While the increase in exogenous exergetic cost parameters of AC, CC and GT is found to be directly proportional to the increase in dead state temperatures, for PL, WD, GD and COGEN this relationship is found to be inversely proportional. These relationships are shown in Figure 5.45 and Figure 5.46 for all components and COGEN, respectively.

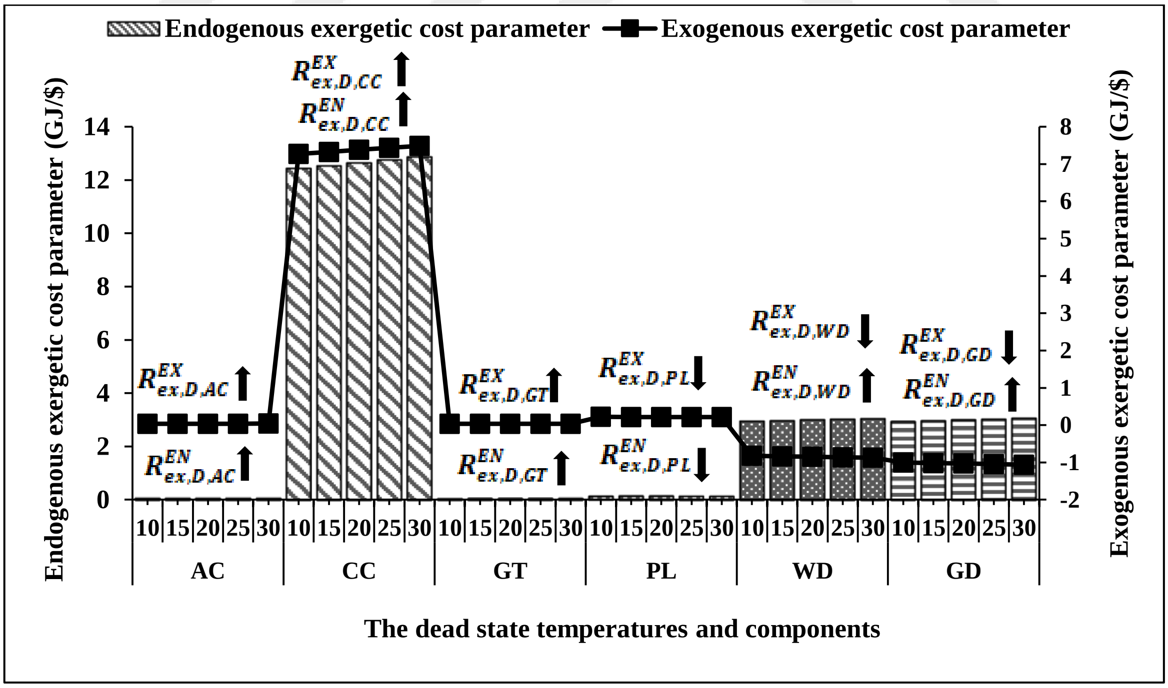


Figure 5.45. Effect of dead state temperatures on endogenous and exogenous exergetic cost parameters of components

Table 5.10. Results of advanced EXCEM for COGEN and its components (GJ/$)

Components	***T*** **(°C)**	$\dot{R}_{ex,D}$	$\dot{R}_{ex,D}^{EN}$	$\dot{R}_{ex,D}^{EX}$	$\dot{R}_{ex,D}^{UN}$	$\dot{R}_{ex,D}^{AV}$	$\dot{R}_{ex,D}^{UN}$		$\dot{R}_{ex,D}^{AV}$	
							$\dot{R}_{ex,D}^{UN,EN}$	$\dot{R}_{ex,D}^{UN,EX}$	$\dot{R}_{ex,D}^{AV,EN}$	$\dot{R}_{ex,D}^{AV,EX}$
AC	**10**	0.0870	0.0506	0.0365	0.0622	0.0250	0.0193	0.0429	0.0313	-0.0064
	15	0.0880	0.0509	0.0376	0.0623	0.0262	0.0193	0.0429	0.0316	-0.0054
	20	0.0900	0.0513	0.0387	0.0625	0.0275	0.0194	0.0431	0.0319	-0.0044
	25	0.0910	0.0516	0.0398	0.0626	0.0288	0.0195	0.0432	0.0322	-0.0034
	30	0.0930	0.0520	0.0408	0.0627	0.0300	0.0195	0.0432	0.0324	-0.0024
CC	**10**	19.7020	12.4279	7.2742	16.0752	3.6270	10.1323	5.9429	2.2957	1.3313
	15	19.8620	12.5353	7.3268	16.2806	3.5815	10.2571	6.0235	2.2782	1.3033
	20	20.0260	12.6448	7.3808	16.4858	3.5398	10.3817	6.1041	2.2631	1.2767
	25	20.1840	12.7516	7.4328	16.6816	3.5028	10.5000	6.1816	2.2516	1.2512
	30	20.3430	12.8584	7.4847	16.8730	3.4701	10.6152	6.2578	2.2432	1.2269
GT	**10**	0.0740	0.0423	0.0318	0.0118	0.0624	0.0067	0.0051	0.0356	0.0268
	15	0.0760	0.0433	0.0326	0.0124	0.0635	0.0071	0.0053	0.0362	0.0272
	20	0.0770	0.0442	0.0332	0.0129	0.0646	0.0074	0.0055	0.0369	0.0277
	25	0.0790	0.0452	0.0340	0.0135	0.0657	0.0077	0.0058	0.0375	0.0282
	30	0.0810	0.0462	0.0347	0.0142	0.0668	0.0081	0.0061	0.0381	0.0287
PL	**10**	0.3520	0.1309	0.2207	0.1202	0.2315	0.0410	0.0792	0.0899	0.1415
	15	0.3490	0.1296	0.2191	0.1195	0.2293	0.0406	0.0789	0.0890	0.1403
	20	0.3460	0.1283	0.2175	0.1188	0.2270	0.0402	0.0786	0.0881	0.1389
	25	0.3430	0.1270	0.2159	0.1181	0.2249	0.0398	0.0783	0.0872	0.1376
	30	0.3400	0.1257	0.2143	0.1174	0.2227	0.0394	0.0780	0.0863	0.1363
WD	**10**	2.1250	2.9474	-0.8221	0.2215	1.9038	0.1488	0.0727	2.7986	-0.8948
	15	2.1360	2.9709	-0.8351	0.2449	1.8909	0.1613	0.0836	2.8096	-0.9187
	20	2.1450	2.9933	-0.8484	0.2673	1.8776	0.1723	0.0950	2.8210	-0.9434
	25	2.1570	3.0185	-0.8613	0.2925	1.8647	0.1838	0.1087	2.8347	-0.9700
	30	2.1690	3.0433	-0.8744	0.3171	1.8519	0.1937	0.1234	2.8497	-0.9978
GD	**10**	1.9380	2.9372	-0.9987	0.4133	1.5252	0.2881	0.1253	2.6491	-1.1239
	15	1.9540	2.9683	-1.0147	0.4461	1.5075	0.3054	0.1408	2.6629	-1.1554
	20	1.9690	2.9996	-1.0310	0.4792	1.4894	0.3214	0.1578	2.6782	-1.1888
	25	1.9850	3.0316	-1.0470	0.5130	1.4716	0.3363	0.1767	2.6953	-1.2237
	30	2.0010	3.0642	-1.0630	0.5473	1.4539	0.3496	0.1977	2.7145	-1.2606
COGEN	**10**	0.8494	0.7666	0.0828	0.4761	0.3733	0.2924	0.1837	0.4742	-0.1009
	15	0.8562	0.7736	0.0826	0.4855	0.3707	0.2978	0.1877	0.4758	-0.1051
	20	0.8631	0.7806	0.0824	0.4948	0.3682	0.3029	0.1919	0.4777	-0.1095
	25	0.8700	0.7878	0.0822	0.5041	0.3659	0.3078	0.1963	0.4800	-0.1141
	30	0.8770	0.7951	0.0820	0.5134	0.3637	0.3125	0.2009	0.4826	-0.1189

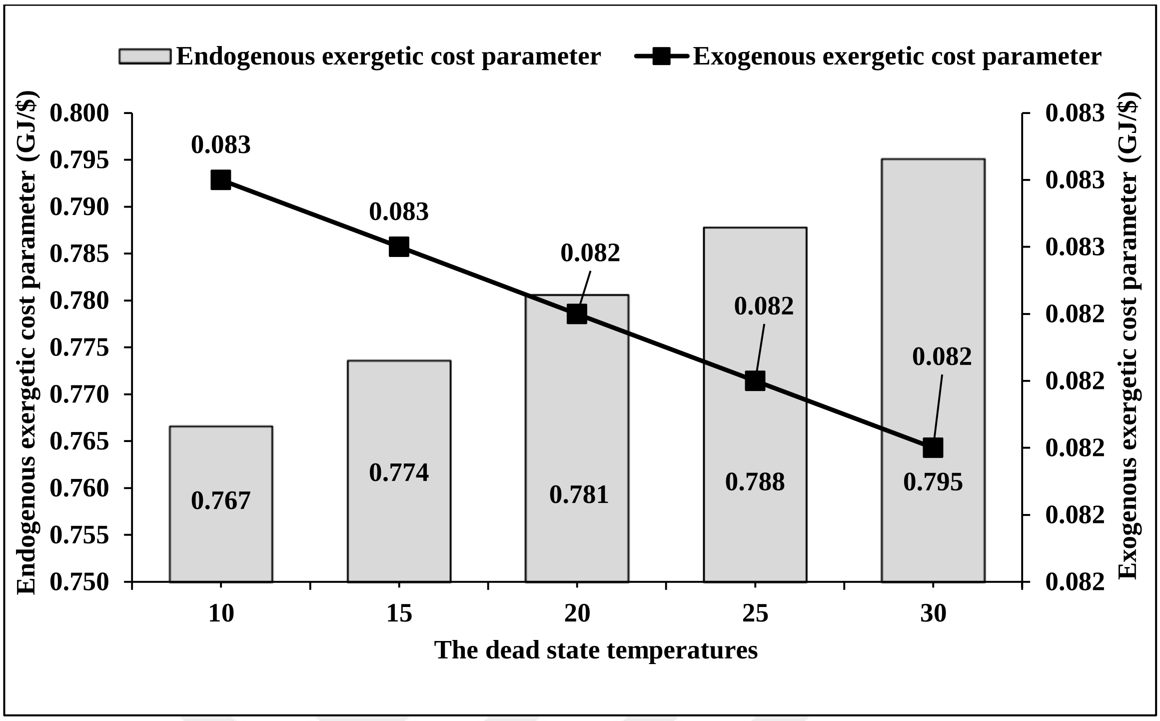


Figure 5.46. Effect of dead state temperatures on endogenous and exogenous exergetic parameters of COGEN

- The unavoidable exergetic cost parameters "$\dot{R}_{ex,D}^{UN}$" of AC, CC and COGEN are higher than their avoidable exergetic cost parameters "$\dot{R}_{ex,D}^{AV}$", while the avoidable exergetic parameters of GT, PL, WD and GD are higher than their unavoidable part. For GT, PL, WD and GD, the exergetic cost parameter can be reduced by replacing the material in which the components are made or by using less costly manufacturing methods. The CC with the highest avoidable exergetic cost parameter is determined in the advanced EXCEM method, where it is the main component to focus on. GT and WD are also the components with the highest rate of avoidable exergetic cost parameters. While the increase in unavoidable exergetic cost factor of PL is determined to be inversely directly proportional to the increase in dead state temperatures, for other components and COGEN, this relationship is found to be directly proportional. In addition, the increase in avoidable exergetic cost parameters of AC and GT is directly proportional to the increase in dead state temperatures, whereas for other components and COGEN, this relationship is inversely proportional. These relationships of components and COGEN are detailed in Figure 5.47 and Figure 5.48, respectively.

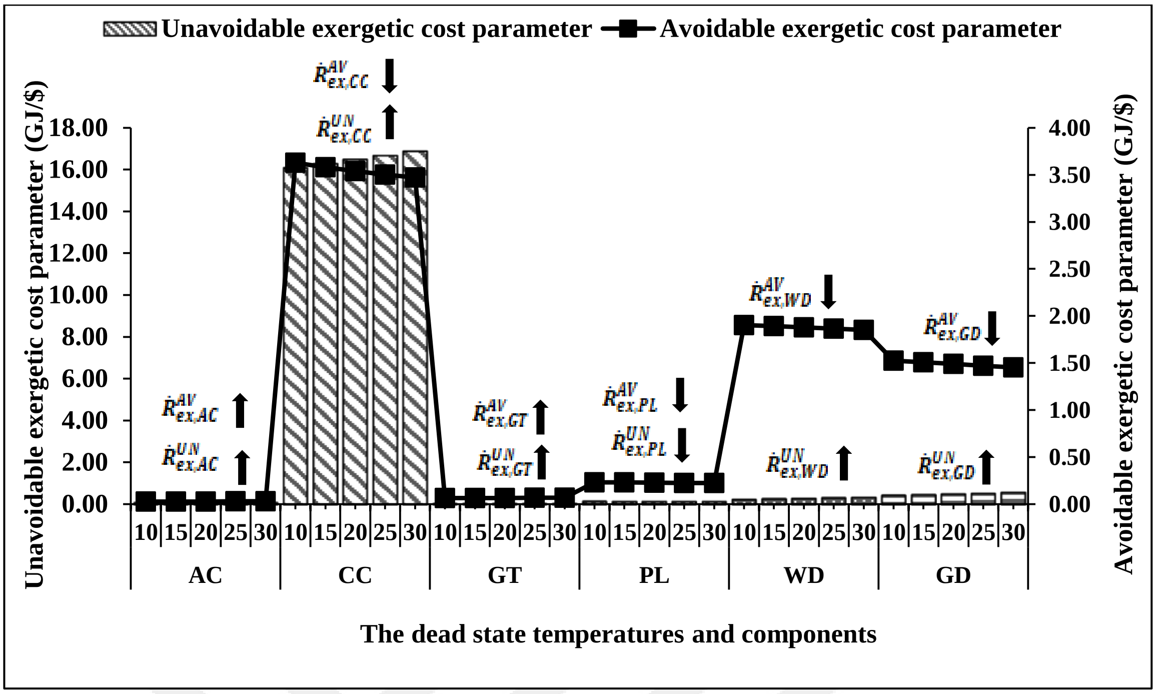


Figure 5.47. Effect of dead state temperatures on unavoidable and avoidable exergetic cost parameters of components

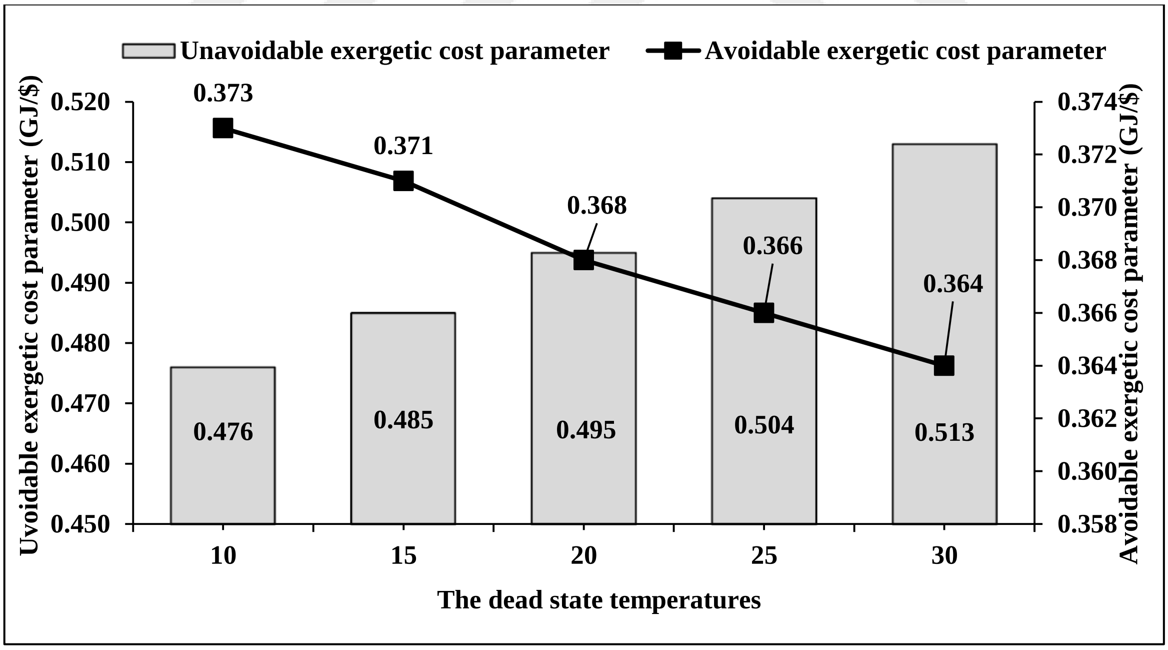


Figure 5.48. Effect of dead state temperatures on unavoidable and avoidable exergetic cost parameters of COGEN

- The avoidable and unavoidable exergetic cost parameter can be divided into endogenous and exogenous parts and the effect of irreversibilities on the component itself or other components can be determined in detail. The fact that unavoidable endogenous exergetic cost parameters "$\dot{R}_{ex,D}^{UN,EN}$" of CC, GT, WD, GD and COGEN are higher than unavoidable endogenic exergetic cost parameters "$\dot{R}_{ex,D}^{UN,EX}$" at all dead state temperatures, which is due to the irreversibilities or structural properties of the components themselves. The unavoidable exogenous exergetic cost parameters for AC and PL are higher than the endogenous parts of parameters, which is a sign that the irreversibilities occurring in other components have a higher effect.

  Avoidable endogenous exergetic cost parameters "$\dot{R}_{ex,D}^{AV,EN}$" of COGEN and its components except PL are higher than their avoidable exogenous exergetic cost parameters "$\dot{R}_{ex,D}^{AV,EX}$", which means that improvements to the components themselves can be more effective. The avoidable and unavoidable exergetic cost parameters into endogenous and exogenous parts for the all components and COGEN are given as Figure 5.49 and Figure 5.50. It is also used in Table 5.11 to better demonstrate the effect of dead state temperatures on combination of avoidable and unavoidable exergetic cost parameters with endogenous and exogenous exergetic cost parameters.

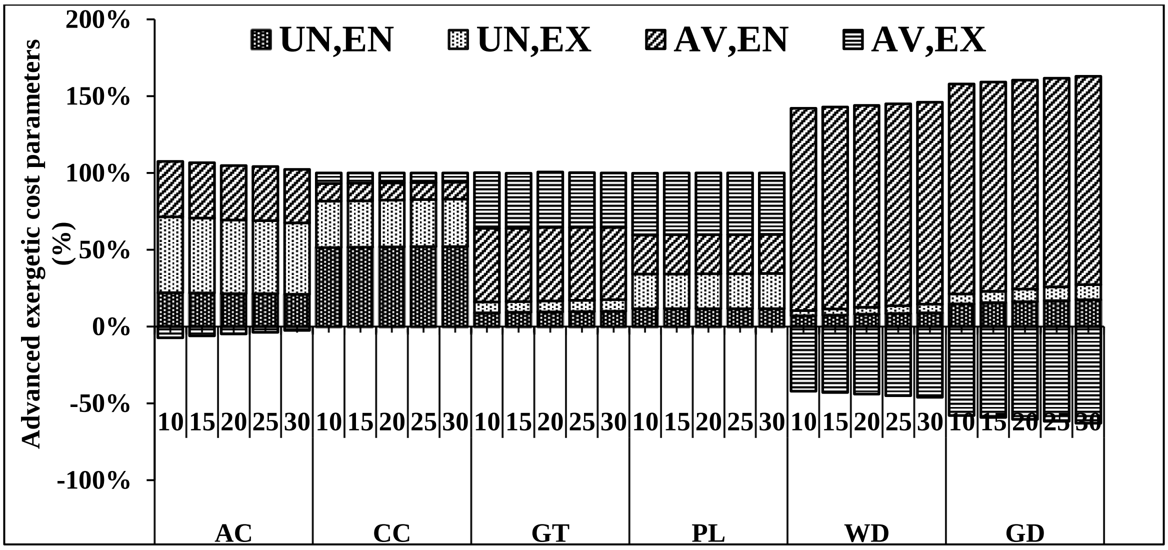


Figure 5.49. Effect of dead state temperatures on avoidable and unavoidable advanced exergetic cost parameter into endogenous and exogenous parts of components

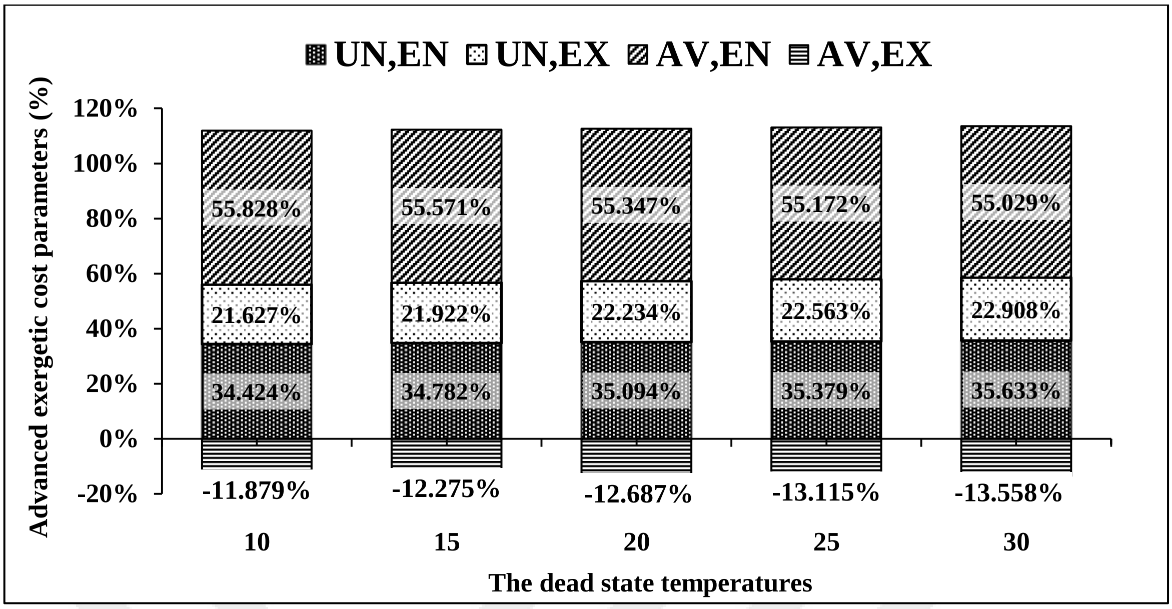


Figure 5.50. Effect of dead state temperatures on avoidable and unavoidable advanced exergetic cost parameter into endogenous and exogenous parts of COGEN

Table 5.11. Effect of dead state temperatures on combination of avoidable and unavoidable exergetic cost parameter with endogenous and exogenous exergetic cost parameter (%)

Components	T(°C)	$\dot{R}_{ex,D}^{UN,EN}$	$\dot{R}_{ex,D}^{UN.EX}$	$\dot{R}_{ex,D}^{AV.EN}$	$\dot{R}_{ex,D}^{AV.EX}$
AC	10	22.184%	49.310%	35.977%	-7.356%
	15	21.932% ↓	48.750% ↓	35.909% ↑	-6.136% ↑
	20	21.556%	47.889%	35.444%	-4.889%
	25	21.429%	47.473%	35.385%	-3.736%
	30	20.968%	46.452%	34.839%	-2.581%
CC	10	51.428%	30.164%	11.652%	6.757%
	15	51.642% ↑	30.327% ↑	11.470% ↓	6.562% ↓
	20	51.841%	30.481%	11.301%	6.375%
	25	52.021%	30.626%	11.155%	6.199%
	30	52.181%	30.761%	11.027%	6.031%
GT	10	9.054%	6.892%	48.108%	36.216%
	15	9.342% ↕	6.974% ↕	47.632% ↕	35.789% ↕
	20	9.610%	7.143%	47.922%	35.974%
	25	9.747%	7.342%	47.468%	35.696%
	30	10.000%	7.531%	47.037%	35.432%

Table 5.11. Effect of dead state temperatures on combination of avoidable and unavoidable exergetic cost parameter with endogenous and exogenous exergetic cost parameter (%) (continued)

Components	**T(°C)**	$\dot{R}_{ex,D}^{UN,EN}$	$\dot{R}_{ex,D}^{UN,EX}$	$\dot{R}_{ex,D}^{AV,EN}$	$\dot{R}_{ex,D}^{AV,EX}$
PL	10	11.648% ↓	22.500% ↑	25.540% ↓	40.199% ↓
	15	11.633%	22.607%	25.501%	40.201%
	20	11.618%	22.717%	25.462%	40.145%
	25	11.603%	22.828%	25.423%	40.117%
	30	11.588%	22.941%	25.382%	40.088%
WD	10	7.002% ↓	3.421% ↓	131.699% ↑	-42.108% ↑
	15	7.551%	3.914%	131.536%	-43.010%
	20	8.033%	4.429%	131.515%	-43.981%
	25	8.521%	5.039%	131.419%	-44.970%
	30	8.930%	5.689%	131.383%	-46.003%
GD	10	14.866% ↑	6.465% ↑	136.692% ↓	-57.993% ↓
	15	15.629%	7.206%	136.279%	-59.130%
	20	16.323%	8.014%	136.018%	-60.376%
	25	16.942%	8.902%	135.783%	-61.647%
	30	17.471%	9.880%	135.657%	-62.999%
COGEN	10	34.424% ↕	21.627% ↕	55.828% ↕	-11.879% ↕
	15	34.782%	21.922%	55.571%	-12.275%
	20	35.094%	22.234%	55.347%	-12.687%
	25	35.379%	22.563%	55.172%	-13.115%
	30	35.633%	22.908%	55.029%	-13.558%

5.6. Evaluation of the System in terms of Advanced Exergoenvironmental Analysis

The exergoenvironmental analysis using conventional exergy analysis results determines the environmental impact of irreversibilities in a system, but cannot determine the environmental impact of irreversibilities caused by interaction between components of that system or the actual improvement potential that can be realized. Therefore, by combining the results of the advanced exergy analysis with the results of the exergoenvironmental analysis, the results of the advanced exergoenvironmental analysis shown in Table 5.12 are obtained. In other words, the results of environmental analysis are divided into endogenous-exogenous, avoidable-unavoidable parts..

Table 5.12. Results of advanced exergoenvironmental analysis (mPts/h) for COGEN and its components

(Components	T (°C)	$\dot{B}_D$	$\dot{B}_D^{EN}$	$\dot{B}_D^{EX}$	$\dot{B}_D^{UN}$	$\dot{B}_D^{AV}$	$\dot{B}_D^{UN}$		$\dot{B}_D^{AV}$	
							$\dot{B}_D^{UN.EN}$	$\dot{B}_D^{UN.AV}$	$\dot{B}_D^{AV.EN}$	$\dot{B}_D^{AV.EX}$
AC	10	18800.527	10918.404	7882.123	13416.114	5384.413	4165.164	9250.950	6753.240	-1368.827
	15	19317.126	11117.859	8199.267	13593.536	5723.590	4221.996	9371.540	6895.863	-1172.273
	20	19903.566	11340.046	8563.520	13823.028	6080.538	4295.030	9527.998	7045.016	-964.478
	25	20437.984	11545.226	8892.758	14005.126	6432.858	4353.415	9651.711	7191.812	-758.954
	30	20987.946	11752.822	9235.124	14188.548	6799.398	4412.261	9776.286	7340.561	-541.163
CC	10	103199.086	65096.751	38102.335	84200.761	18998.325	53072.237	31128.524	12024.514	6973.811
	15	104025.370	65651.439	38373.931	85266.788	18758.582	53719.894	31546.893	11931.545	6827.037
	20	104868.750	66216.550	38652.200	86330.783	18537.967	54365.633	31965.149	11850.917	6687.050
	25	105685.086	66767.316	38917.770	87345.176	18339.910	54978.070	32367.106	11789.245	6550.665
	30	106503.793	67318.124	39185.669	88335.707	18168.086	55574.206	32761.501	11743.919	6424.167
GT	10	12638.495	7214.161	5424.334	2011.223	10627.272	1148.151	863.072	6066.011	4561.261
	15	13069.805	7462.624	5607.181	2140.018	10929.787	1221.677	918.341	6240.947	4688.840
	20	13497.357	7706.825	5790.532	2247.765	11249.592	1283.192	964.573	6423.633	4825.959
	25	13949.806	7965.159	5984.647	2384.091	11565.715	1361.027	1023.065	6604.133	4961.582
	30	14409.434	8227.965	6181.469	2523.565	11885.869	1440.662	1082.903	6787.303	5098.566
PL	10	8608.158	3206.224	5401.934	2942.993	5665.165	1004.341	1938.652	2201.884	3463.281
	15	8635.410	3209.140	5426.270	2957.583	5677.827	1005.338	1952.245	2203.802	3474.025
	20	8660.965	3213.137	5447.828	2974.143	5686.822	1006.534	1967.609	2206.603	3480.219
	25	8679.429	3215.068	5464.361	2988.541	5690.888	1007.209	1981.331	2207.858	3483.030
	30	8696.657	3216.459	5480.198	3002.811	5693.846	1007.710	1995.101	2208.750	3485.096

Table 5.12. Results of advanced exergoenvironmental analysis (mPts/h) for COGEN and its components (continued)

Components	T (°C)	$\dot{B}_D$	$\dot{B}_D^{EN}$	$\dot{B}_D^{EX}$	$\dot{B}_D^{UN}$	$\dot{B}_D^{AV}$	$\dot{B}_D^{UN}$		$\dot{B}_D^{AV}$	
							$\dot{B}_D^{UN.EN}$	$\dot{B}_D^{UN.AV}$	$\dot{B}_D^{AV.EN}$	$\dot{B}_D^{AV.EX}$
WD	10	46868.818	64994.692	-18125.874	4884.693	41984.125	3281.016	1603.677	61713.677	-19729.552
	15	47934.062	66673.181	-18739.119	5496.284	42437.778	3619.469	1876.815	63053.711	-20615.933
	20	49175.800	68626.333	-19450.533	6127.680	43048.120	3949.952	2177.728	64676.382	-21628.262
	25	50482.239	70638.017	-20155.778	6845.730	43636.509	4301.093	2544.637	66336.924	-22700.415
	30	51914.721	72840.601	-20925.880	7588.954	44325.767	4635.206	2953.748	68205.395	-23879.628
GD	10	57679.363	87396.226	-29716.863	12298.056	45381.307	8571.035	3727.021	78825.191	-33443.884
	15	58837.555	89397.221	-30559.666	13436.489	45401.066	9196.655	4239.834	80200.565	-34799.499
	20	60174.599	91690.629	-31516.030	14647.892	45526.707	9824.865	4823.026	81865.764	-36339.057
	25	61444.925	93857.824	-32412.899	15882.382	45562.543	10412.520	5469.862	83445.304	-37882.761
	30	62771.217	96115.698	-33344.481	17167.293	45603.924	10966.978	6200.315	85148.721	-39544.797
COGEN	10	236648.168	225917.396	10728.844	116851.042	119795.683	69813.301	47037.636	156104.106	-36308.800
	15	240410.189	230275.969	10132.682	119830.193	120578.352	71473.404	48356.789	158802.296	-38224.214
	20	244568.101	235174.806	9389.630	122922.064	121642.591	73129.602	49792.243	162045.436	-40402.834
	25	248668.071	239995.375	8675.977	126046.459	122624.765	74735.335	51311.252	165260.219	-42635.624
	30	252954.257	245075.936	7880.268	129219.893	123736.312	76278.887	52941.006	168797.235	-45060.923

In the scope of advanced exergoenvironmental analysis in this study, the component-related environmental impact rate is not divided into endogenous-exogenous and avoidable-unavoidable parts. Because, as shown in Table 5.3, the ratio of the component-related environmental impact rate of any component to the total environmental impact rate of that component is very low (below 1%). Therefore, there is no need to calculate the advanced exergoenvironmental factor in this study. The following inferences can be made according to the results of advanced exergoenvironmental analysis:

- The endogenous environmental impact rate "$\dot{B}_D^{EN}$" of COGEN and its components except PL is higher than their exogenous environmental impact rate "$\dot{B}_{D,}^{EX}$". The main reason for this can be said to be the irreversibility of the components due to their own operating conditions. Therefore, the relationship between the other components except PL is weak in terms of environmental impact. Although CC has the highest endogenous exergy destruction value, GD (96115.698 mPts/h at 30 °C) has the highest environmental impact rate because its specific environmental impact rate is higher than CC. In contrast, while the highest endogenous environmental impact rate is calculated for the CC (67318.124 at 30 °C), the exogenous environmental impacts of GD and WD are negative because their exogenous exergy destruction values are negative. The increase in endogenous environmental impact rates of all components is found to be directly proportional to the increase in dead state temperatures. Furthermore, the increase in exogenous environmental impact rates of AC, CC, GT and PL is directly proportional to the increase in dead state temperatures, whereas for WD, GD, and COGEN this relationship is inversely proportional. The results of endogenous and exogenous exergoenvironmental are illustrated in Figure 5.51 and Figure 5.52, respectively.

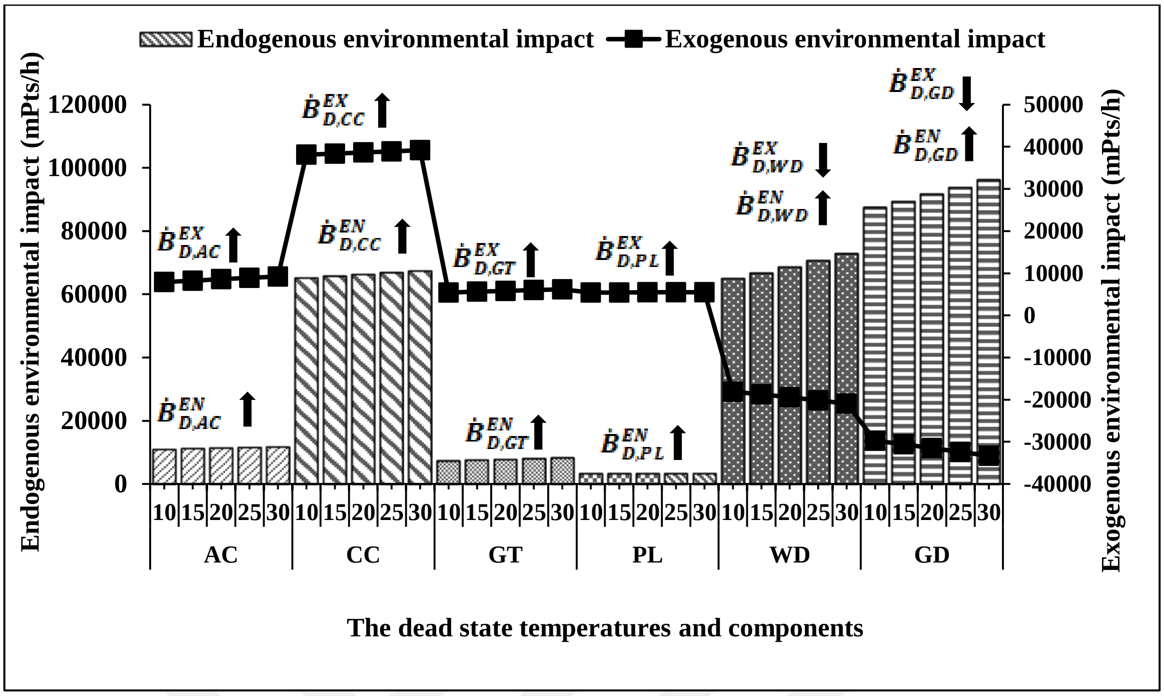


Figure 5.51. Effect of dead state temperatures on endogenous and exogenous environmental impact rates of components

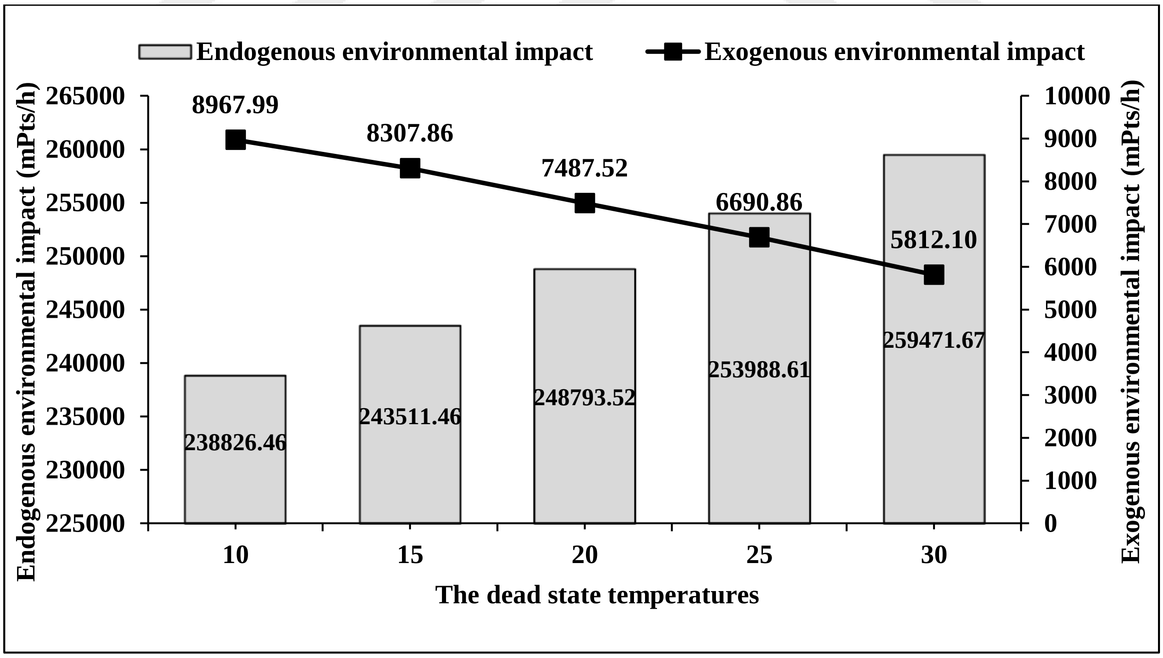


Figure 5.52. Effect of dead state temperatures on endogenous and exogenous environmental impact rates of COGEN

- Because the avoidable environmental impact rate “$\dot{B}_D^{AV}$” of COGEN and its component except AC and CC is higher than their unavoidable environmental impact rate “$\boldsymbol{\dot{B}_{D,WD}^{UN}}$”, the improvement potential of these components is higher in terms of environmental impact. Therefore, it should be focused first, especially on the WD (44325.767 at 30°C) and GD (45603.924 at 30°C), which have the highest avoidable environmental impact rate. Furthermore, the avoidable environmental impacts of WD and GD account for approximately 32% and 34% of the avoidable environmental impact rate of COGEN, respectively. The higher unavoidable environmental impact rate occurring in CC (88335.707 mPts/h at 30 °C), which cannot be reduced by any technological development, accounts for more than 66.5% of the unavoidable environmental impact rate occurring in COGEN. The increase in the unavoidable environmental impact rates of COGEN and its all component is directly proportional to the increase in dead state temperatures. For an increase in avoidable environmental impact, this relationship is directly proportional to other components except CC. These relationships for components and COGEN are given in Figure 5.53 and Figure 5.54, respectively.

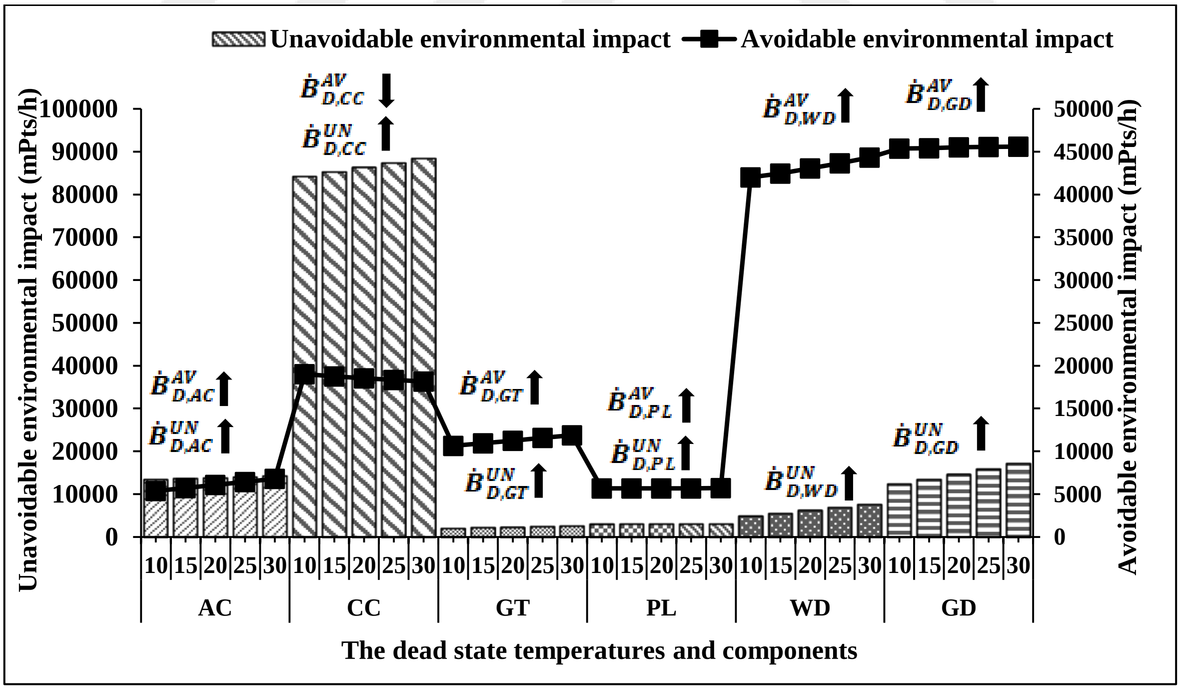


Figure 5.53. Effect of dead state temperatures on unavoidable and avoidable environmental impact rate of components

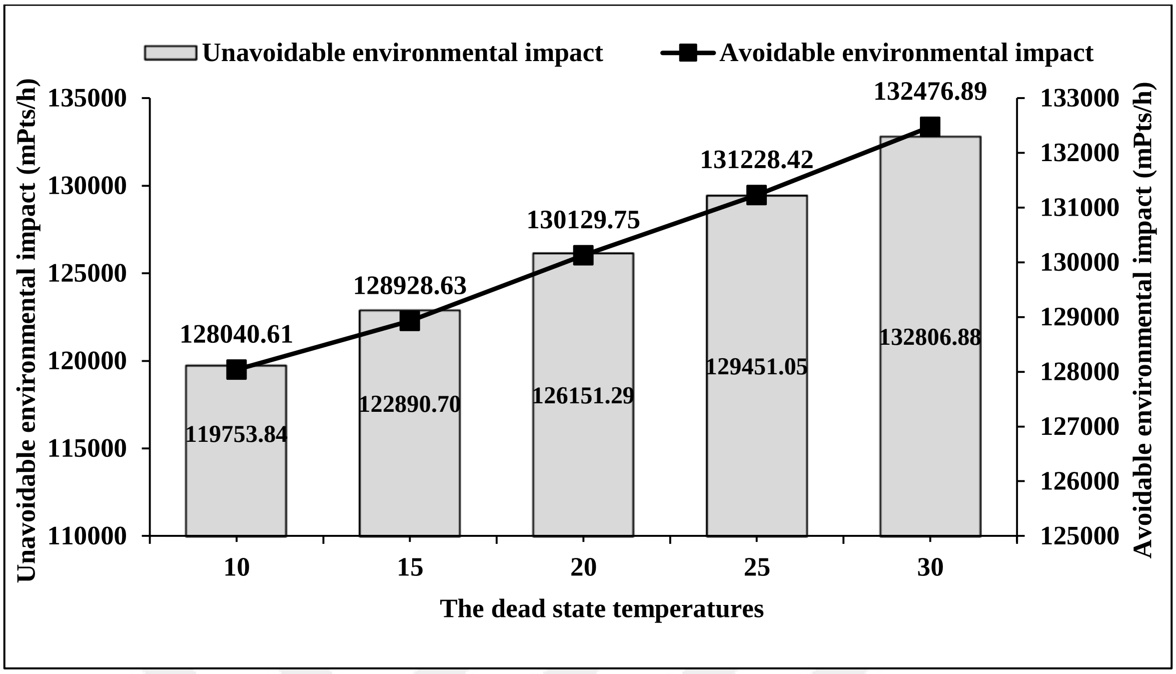


Figure 5.54. Effect of dead state temperatures on unavoidable and avoidable environmental impact rate of COGEN

- In COGEN and its all components except AC and PL, the unavoidable endogenous environmental impact rate “$\dot{B}_D^{UN,EN}$” is higher than the unavoidable exogenous environmental impact rate “$\dot{B}_D^{UN,EX}$”. In particular, the unavoidable endogenous and exogenous environmental impact rate of CC accounts for more than 71.9% and 59.8% of COGEN, respectively. In this component where combustion reactions occur, the effect of irreversibilities can be seen once again in environmental analysis. Besides, in all components except PL, the avoidable endogenous environmental impact rate“$\dot{B}_D^{AV,EN}$” is higher than the avoidable exogenous environmental impact rate “$\dot{B}_D^{AV,EX}$”. WD and GD, which have the highest avoidable endogenous environmental impact rate, account for more than 36.8% and 46.9% of the COGEN’s avoidable endogenous environmental impact, respectively. Therefore, with the help of technological improvements in these components, the environmental impact rate can be reduced by reducing their irreversibility. The avoidable and unavoidable exergetic cost parameters into endogenous and exogenous parts for the all components and COGEN are given as Figure 5.55 and Figure 5.56. It is also used in Table 5.13 to better demonstrate the effect of dead state temperatures on combination of avoidable and unavoidable exergetic cost parameters with endogenous and exogenous exergetic cost parameters.

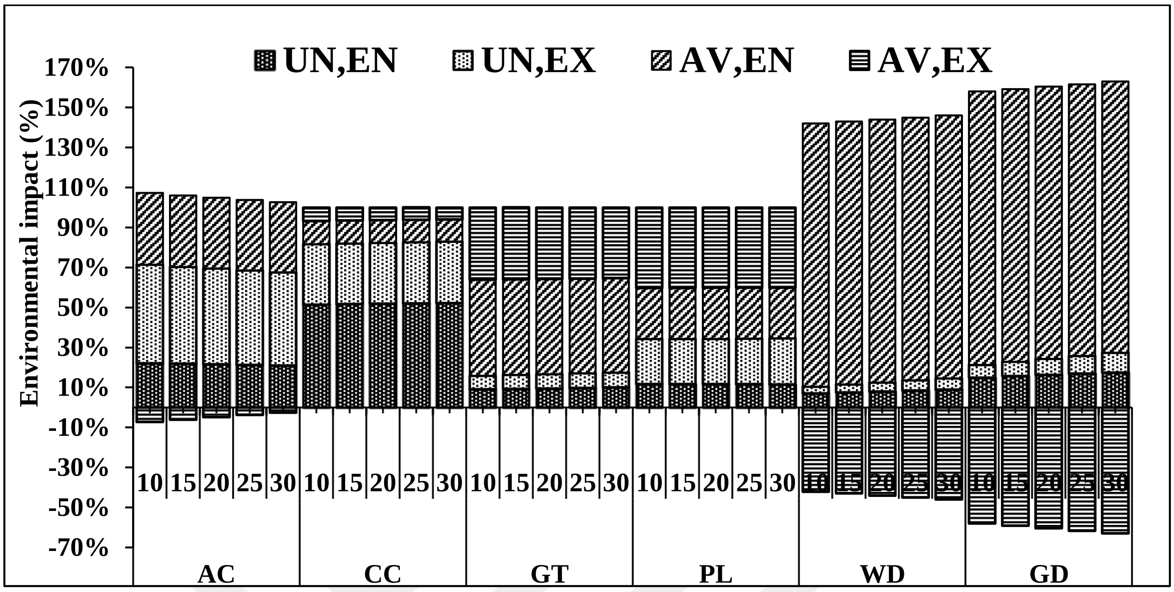


Figure 5.55. Effect of dead state temperatures on avoidable and unavoidable environmental impact rate into endogenous and exogenous parts of components

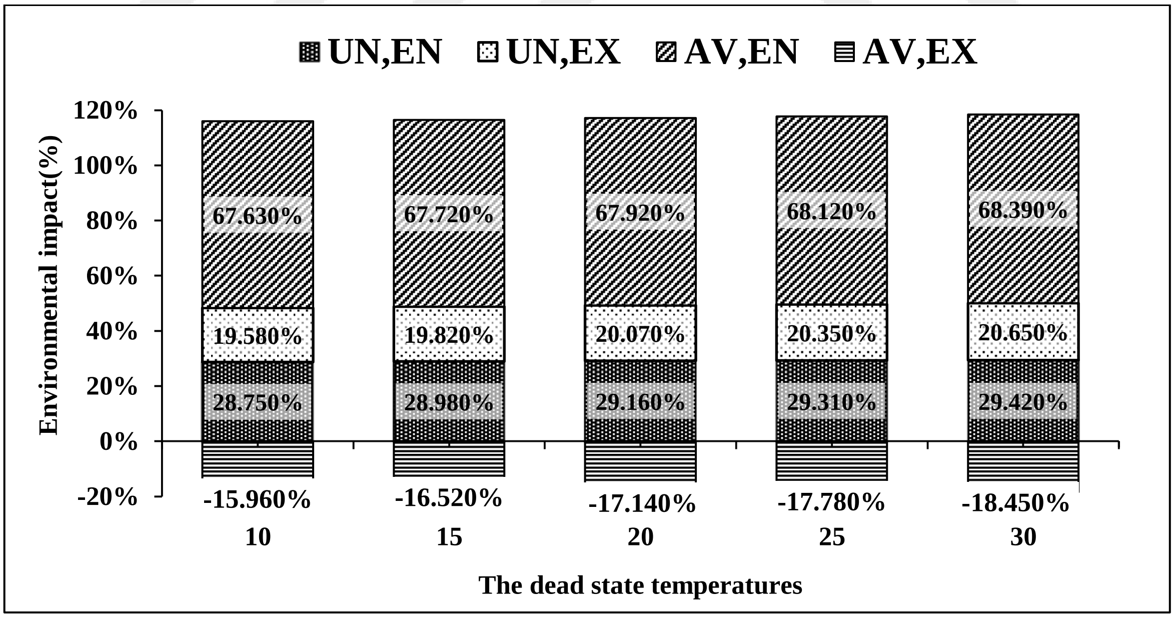


Figure 5.56. Effect of dead state temperatures on avoidable and unavoidable environmental impact rate into endogenous and exogenous parts of COGEN

Table 5.13. Effect of dead state temperatures on combination of avoidable and unavoidable environmental impact rate with endogenous and exogenous environmental impact rate (%)

Components	***T*(°C)**	$\dot{B}_D^{UN,EN}$		$\dot{B}_D^{UN,EX}$		$\dot{B}_D^{AV,EN}$		$\dot{B}_D^{AV,EX}$	
AC	10	22,15%	↓	49,21%	↓	35,92%	↓	-7,28%	↑
	15	21,86%		48,51%		35,70%		-6,07%	
	20	21,58%		47,87%		35,40%		-4,85%	
	25	21,30%		47,22%		35,19%		-3,71%	
	30	21,02%		46,58%		34,98%		-2,58%	
CC	10	51,43%	↑	30,16%	↑	11,65%	↓	6,76%	↓
	15	51,64%		30,33%		11,47%		6,56%	
	20	51,84%		30,48%		11,30%		6,38%	
	25	52,02%		30,63%		11,16%		6,20%	
	30	52,18%		30,76%		11,03%		6,03%	
GT	10	9,08%	↑	6,83%	↑	48,00%	↓	36,09%	↓
	15	9,35%		7,03%		47,75%		35,88%	
	20	9,51%		7,15%		47,59%		35,75%	
	25	9,76%		7,33%		47,34%		35,57%	
	30	10,00%		7,52%		47,10%		35,38%	
PL	10	11,67%	↓	22,52%	↑	25,58%	↓	40,23%	↓
	15	11,64%		22,61%		25,52%		40,23%	
	20	11,62%		22,72%		25,48%		40,18%	
	25	11,60%		22,83%		25,44%		40,13%	
	30	11,59%		22,94%		25,40%		40,07%	
WD	10	7,00%	↑	3,42%	↑	131,67%	↓	-42,10%	↓
	15	7,55%		3,92%		131,54%		-43,01%	
	20	8,03%		4,43%		131,52%		-43,98%	
	25	8,52%		5,04%		131,41%		-44,97%	
	30	8,93%		5,69%		131,38%		-46,00%	
GD	10	14,86%	↑	6,46%	↑	136,66%	↓	-57,98%	↓
	15	15,63%		7,21%		136,31%		-59,15%	
	20	16,33%		8,02%		136,05%		-60,39%	
	25	16,95%		8,90%		135,81%		-61,65%	
	30	17,47%		9,88%		135,65%		-63,00%	
COGEN	10	28,75%	↑	19,58%	↑	67,63%	↑	-15,96%	↓
	15	28,98%		19,82%		67,72%		-16,52%	
	20	29,16%		20,07%		67,92%		-17,14%	
	25	29,31%		20,35%		68,12%		-17,78%	
	30	29,42%		20,65%		68,39%		-18,45%	

5.7. Economic Assessment of Cogeneration System (COGEN) through NPV Method

In the cogeneration system modeled for the ceramic factory, the gas turbine unit and the pipe line are assumed as the new investment. Therefore, these two systems are taken into account as this initial cost. Labor is costed by predicting that a team of four people will work in the gas turbine unit. The interest rate was assumed to be 10% annually, as in the exergoeconomic analysis. In order for the gas turbine cogeneration system to be accepted according to this method, the net present value must be equal to or greater than zero. According to the net present value results shown in Table 5.14, it is determined that the system reached its breakeven point in the 13th year. The reasons that affect the breakeven point of the investment:

- The high maintenance cost of the gas turbine
- Fluctuations in electricity and natural gas prices
- Inefficient use of the resulting thermal energy
- Increases in interest rates

According to the NPV method, the cogeneration system has a total profit of \$562148 at the end of its lifetime (25 years). The system can't be said to be very profitable in the long term or in the short term. However, since it can provide uninterrupted electrical energy for the production processes in the ceramic sector, there is an increase in quality, capacity and efficiency as opposed to a decrease. This increases the ability to compete in the global market by causing reductions in product cost. Also, thanks to this cogeneration system, it can be said that the environmental impact of ceramic production is reduced.

Table 5.14. Result of NPV for COGEN

Years	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Initial investment cost ($)	-1874139													
Benefit per year ($)		513680	513679	513679	513679	513679	513679	513679	513679	513679	513679	513679	513679	513679
Maintenance and repair costs		-223245	-223245	-223245	-223245	-223245	-223245	-223245	-223245	-223245	-223245	-223245	-223245	-223245
Labour cost per year ($)		-24200	-24200	-24200	-24200	-24200	-24200	-24200	-24200	-24200	-24200	-24200	-24200	-24200
Interest rate	10.00%	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Net cash flow ($)	-1874139	266235	266234	266234	266234	266234	266234	266234	266234	266234	266234	266234	266234	266234
Discount rate	1	0.909	0.826	0.751	0.683	0.621	0.564	0.513	0.467	0.424	0.386	0.350	0.319	0.290
Discounted net cash flow ($)	-1874139	242032	220028	200026	181841	165310	150282	136620	124200	112909	102645	93313	84830	77119
NPV ($)		-1632107	-1412079	-1212054	-1030212	-864902	-714620	-578000	-453800	-340890	-238246	-144932	-60102	17017

6. CONCLUSIONS

In this study, a natural gas-fired and gas turbine cogeneration system is modeled in a ceramic plant located in the organized industrial zone, and a thermodynamic evaluation of that system is provided with the help of exergy and advanced exergy analysis before such a large investment. Due to the nature of the ceramic factories, considering the working conditions change seasonally, five different dead state temperatures are selected. Thus, the exergetic effects of the dead state temperatures on the components and the overall system can be determined. In addition, exergoeconomic and exergoenvironmental analyses of this modeled cogeneration system are carried out to obtain information about the system in terms of economic and environmental impact. In addition to all these, advanced exergy analysis is carried out for this modeled system and the relationships of the components with each other, the improvement potentials that can be realized, and the effects of technological and economic constraints are determined.

The results of conventional and advanced exergy analysis for this modeled cogeneration system can be listed as follows:

- CC is the first component to focus on, as it has the highest exergy destruction value “$\dot{E}x_D$” (10058.532 kW at 30°C) and the highest exergy improvement potential “$\dot{E}xI\dot{P}$” (4786.854 kW at 30 °C). Furthermore, the relative exergy consumption rate “ϕ” of this component is more than 48%. In this component where chemical reactions occur, as expected, it is the component with the highest endogenous exergy destruction value “$\dot{E}x_D^{EN}$” (6357.772 kW at 30 °C). In addition, the avoidable exergy destruction value “$\dot{E}x_D^{AV}$” (1793.320 kW at 10 °C) that can be prevented with the help of technological and physical improvements in this component is very low compared to the unavoidable exergy destruction value “$\dot{E}x_D^{UN}$”of that component (8342.750 kW at 30°C), but it is one of the components that has the highest improvement potential among the components. For this component, an increase in the dead state temperature causes an increase in the exergy destruction value, while a decrease in avoidable exergy destruction value.

- The lowest exergy efficiency rates "ψ" are calculated at the WD (17.430% at 30 °C) and GD (23.131% at 30 °C). In addition, WD (2280.872 kW at 10 °C) and GD (2602.603 kW at 10 °C) have the highest avoidable exergy destruction "$\dot{E}x_D^{AV}$" value among components. All of the avoidable exergy destruction of these components consists of endogenous exergy destruction "$\dot{E}x_D^{AV,EN}$". Therefore, all of the exergy destruction of these components results from the irreversibilities within them. In addition, they have the highest avoidable exergy destruction among the components, which can be most beneficial when focused on them.
- Because the exergy efficiencies of the other components (AC, GT, PL) in the COGEN is very high and the exergy destruction values of these components is relatively low for the other components (CC, WD, GD), it is not necessary to focus on them.
- Since the endogenous exergy destruction value of the COGEN is higher than its exogenous exergy destruction value, the relationship between the components is seen to be weak. It is also determined that the unavoidable exergy destruction value of the system is higher than the avoidable exergy destruction, especially because improvement potential of CC is very low.
- The dead state temperature increase negatively affects the exergy destruction of COGEN and the endogenous exergy destruction (providing an increase), while also reducing the avoidable exergy destruction.

The results of conventional and advanced exergoeconomic analysis for this modeled cogeneration system can be listed as follows:

- Although CC (6.97 $/GJ) has the lowest unit fuel exergy cost "c_f" among components, its exergy destruction cost rate "$\dot{C}_D$" (252.391 $/h at 30 °C) is the highest, which is because the highest exergy destruction value occurs again in this component. More than 17% of exergy destruction cost rate of CC consists of avoidable exergy destruction cost rate "$\dot{C}_D^{AV}$", while 11% of it consists of avoidable endogenous exergy destruction cost "$\dot{C}_D^{AV,EN}$". In addition, the fact that the unavoidable exergy destruction cost rate "$\dot{C}_D^{UN}$" of COGEN ratio is more than 66% in CC reveals the negative impact of this component on COGEN.

- In exergoeconomic analysis, the primary focus for researchers is on components with a highest rate of avoidable exergy destruction “$\dot{C}_D^{AV}$”. In this cogeneration system, it is concluded that the first focus should be on the components WD (105.541 \$/h at 30 °C) and GD (107.499 \$/h at 30 °C), which have the highest avoidable exergy destruction cost rate, all of which occur from avoidable endogenous exergy destruction cost rate “$\dot{C}_D^{AV,EN}$”. In addition, more than 67% of the exergy destruction cost rate of COGEN is due to these two components. The design and technological improvements to be made especially for these components can lead to positive results in terms of reducing the exergy destruction cost rate of the COGEN. Also, the low exergy efficiency “ψ” of these two components causes the highest relative cost difference “r_k”.
- Since more than 96% of the exergy destruction cost rate of the COGEN consists of endogenous exergy destruction cost, it is determined that the components have very weak relations with each other in terms of exergy destruction cost rate.
- The AC (40.563% at 10 °C), which has the highest exergoeconomic factor “f_k” after GT (46.461% at 10 °C), has been found to have a very low its modified exergoeconomic factor “$f^{AV,EN}$” (0.880% at 30 °C), as the avoidable endogenous investment cost rate “$\dot{Z}^{AV,EN}$” is very low (0.159 \$/h at 30 °C). Therefore, after the GT (22.404% at 30 °C), which has the highest modified exergoeconomic factor, it can focus on investment cost rate of WD (1.540% \$/h at 10 °C) and GD (1.670% \$/h at 10 °C).
- As expected, the exergetic cost parameter “$\dot{R}_{ex,D}$” of CC (20.343 \$/h at 30 °C), which has the highest exergy destruction value and the lowest investment cost rate among components, is the highest. However, in terms of investment cost, it is understood that since the avoidable endogenous exergetic cost parameters “$\dot{R}_{ex,D}^{AV,EN}$” of WD (2.8497 \$/h at 30 °C), and GD (2.7145 \$/h at 30 °C), are larger than that of CC (2.2957 \$/h at 10 °C), once again the focus should be on these components.

The results of conventional and advanced exergoenvironmental analysis for this modeled cogeneration system can be listed as follows:

- Among components, although CC (106503.793 mPts/h at 30 °C) has the highest environmental impact rate “$\dot{B}_D$”, WD (51914.721 mPts/h at 30 °C) and GD

(62771.217 mPts/h at 30 °C) have a higher avoidable environmental impact rate "$\dot{B}_D^{AV}$". Therefore, as with exergoeconomic analysis, it is more logical to focus on these components first in terms of environmental impact. The main reason for this is that, as mentioned in the comments for advanced exergy analysis, the actual chemical reactions in the combustion chamber are much higher than those in WD and GD. This indicates that the irreversibilities in the combustion chamber are at a level that cannot be prevented by technological improvements.

- The endogenous environmental impact rate of the cogeneration system is found to be higher than the exogenous environmental impact rate. The main reason for this is that the endogenic environmental impact rates of components such as CC, WD and GD, which have the highest environmental impact rate, are higher than the exogenous parts. Therefore, for the COGEN, it can be said that the components have weak relations with each other in terms of environmental impact.
- In this study, it is understood that in order to reach breakeven point in a short time, besides investment costs, labor costs, interest rates depending on economic stability in the country, variable energy costs and maintenance and repair costs are effective.

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