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Exergoeconomic Analysis of an Industrial Cogeneration Cooling System Powered by Natural Gas Fueled Diesel Engine

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ABSTRACT

This study presents the exergy and exergoeconomic analysis of a natural gas-powered diesel cogeneration system. The cogeneration system is designed for a sports complex with 1000 m2 closed area in Afyonkarahisar city. Natural gas is used as the fuel in the cogeneration system of the sports complex, which includes a swimming pool and ice rink. The natural gas diesel engine is used as the primary energy source for the cogeneration system. In the system, the electricity required for the cooling cycle is produced from the natural gas diesel engine. At the same time, the engine exhaust gases are used in the process of heat generation for swimming pool water heating. Finally, the waste heat discharged from the system is used to produce electricity in the thermoelectric power unit. The cogeneration system was modeled thermodynamically by the EES program on a computer and then economically analyzed by using the Aspen Plus program. The operation of the cogeneration system is described in detail, and a methodology based on exergoeconomic relations and SPECO method is provided to allocate cost flows through subcomponents of the system. The results were compared by using thermodynamic and exergoeconomic performance parameters. The exergetic efficiency of the cogeneration system is found to be 28.74%, which indicates that 71.26% of the total exergy input to the system, mainly by natural gas, is destroyed. As a result of the economic analysis of the cogeneration system, the investment cost was calculated as 62,000 $. The exergetic cost rate and the specific unit exergetic cost of the power produced in the cogeneration system are calculated to be 0.75 $/h and 10.93 $/GJ (0.039 $/kWh), respectively. The specific unit exergetic cost of the energy produced in the cogeneration system for cooling the ice rink and heating the swimming pool in the sports complex are calculated to be 6.152 $/GJ (0.022 $/kWh) and 4.221 $/GJ (0.0152 $ /kWh), respectively.

Keyword: Cogeneration, Thermodynamic analysis, Exergoeconomic analysis

Doğal Gaz Yakıtı Kullanan Dizel Motorlu Endüstriyel Kojenerasyon Soğutma Sisteminin Eksergoekonomik Analizi

ÖZET

Bu çalışmada doğal gaz beslemeli bir dizel kojenrasyon sisteminin ekserji ve exergoeconomic analiz sunulmaktadır. Bu kojenerasyon sistemi uygulaması Afyonkarahisar'da 1000 m2 kapalı alana sahip bir spor kompleksi için planlanmaktadır. Yüzme havuzu ve buz pisti içeren bu spor kompleksinin kojenerasyon sisteminde yakıt olarak doğal gaz kullanılmaktadır. Kojenerasyon sistemine enerji saylamak için doğal gazlı dizel motoru kullanılmıştır. Sistemde soğutma çevrimi için gerekli elektrik doğalgaz motorundan üretilmektedir. Aynı zamanda egzoz gazları yüzme havuzu su ısıtması için proses ısı üretiminde kullanılmaktadır. Son olarak, çevrimlerden atılan atık ısılar termoelektrik devreye gönderilerek elektrik üretilmektedir. Kojenerasyon sistemi bilgisayar ortamında EES programı ile termodinamik olarak modellenmiştir ve daha sonra Aspen Plus programı kullanılarak ekonomik analizi yapılmıştır. Kojenerasyon sistemi detaylı bir şekilde tanıtılmış ve özgül ekserji

maliyetlendirme (SPECO) yöntemi temelinde, sistem bileşenlerinin maliyet akışlarını ifade eden ilişkiler geliştirilmiştir. Elde edilen sonuçlar termodinamik ve eksergoekonomik performans parametreleri kullanılarak karşılaştırılmıştır. Kojenerasyon sisteminin ekserji verimi %28.74 olarak bulunmuştur, bu da sisteme doğalgazla giren ekserjinin %71.26'sının yıkıma uğradığını göstermektedir. Kojenerasyon sisteminin ekonomik analizi sonucunda yatırım maliyeti 62,000 $ olarak hesaplanmıştır. Doğalgaz motorlu kojenerasyon sisteminde üretilen elektriğin ekserjiye bağlı maliyet oranı ve birim ekserji maliyeti sırasıyla, 0.75 $/h ve 10.93 $/GJ (0.039 $/kWh) olarak hesaplanmıştır. Buz pistinin soğutulması ve spor kompleksi içindeki yüzme havuzunun ısıtılması için kojenerasyon sisteminde üretilen enerjinin maliyeti, sırasıyla 6.152 $/GJ (0.022 $/kWh) ve 4.221 $/GJ (0.0152 $/kWh) olarak hesaplanmıştır.

Anahtar Kelimeler: Kojenerasyon, Termodinamik analiz, Eksergoekonomik analiz

I. INTRODUCTION

Industrial sectors are the first place in electricity consumption. In developing countries, the requirement for electricity is increasing rapidly, and it is expected that this increase will continue in the future. The governments review energy policies to encourage investors for electricity production. In this respect, attractive economic opportunities for industrial enterprises that want to produce their electricity are possible with combined heat and power generation (cogeneration), which enables energy savings. Cogeneration is a simple expression of combined heat and power generation (CHP) and is a highly efficient system that allows the production of electricity and heat from a single fuel source [1]. The energy used in the installation of these systems is electricity. Because of the electricity bill, approximately three times more than the heating bill. Cogeneration systems have many advantages over conventional systems. The most important ones are both high efficiency and the reduction of waste emissions resulting from combustion to minimum levels.

It is determined that the efficiency in electricity production in conventional power generation systems is approximately 40%, efficiency in heat boilers is 90%, and total energy efficiency is about 60%. In the cogeneration system, 40-45% of the energy efficiency in the electricity generation and 45-50% in heat energy production showed that the total energy efficiency is 85-90%. Both converting waste heat can demonstrate the difference in efficiency between cogeneration and conventional systems to usable energy and minimizing losses since energy production in cogeneration systems is in the vicinity of the consumption site. The energy savings to be made by providing the electrical energy and thermal energy required for both industrial and residential heating from the same source will reduce our environmental and external dependence. Therefore, the cogeneration method, which is the source of electricity and heat energy from the same source, is required [2]. Also, the capacity of fossil fuels decreases, and the cost of production requirements the use of high-efficiency cogeneration systems because the costs of the reserve are changing every day. Cogeneration systems also vary in the fuels used. So these systems can work with individual gases such as natural gas, biogas, propane, hydrogen, wood gas, and diesel fuel. Natural gas and propane from individual gases are standard and commercialized.

The most important problem for power generation is environmental pollution from the emissions of toxic exhaust gases and other toxic compounds. Power generation and cogeneration systems can be a great danger to human health and living organisms according to the levels of these emissions. Cogeneration or combined heat and power generation system is a preferred technology by many industrial enterprises all over the world since the beginning of the twentieth century because industrial enterprises have economic advantages in compensation for their energy requirements. Cogeneration decreases the use of fuel according to separate heat and power generation facilities and therefore reduces the air and other environmental emissions, thus increasing the energy utilization efficiency. Cogeneration systems driven by rotary piston engines are generally preferred for power generation in the range of 2.5 to 50 MW. These systems are commonly used because of the simple installation and

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package system solutions. The engines used in the production of electricity are reciprocating, internal combustion engines, turbocharged, intercooler industrial engines, and generally consist of standard diesel engines. Heavy diesel fuel is often preferred as fuel. Natural gas, diesel, LPG, propane, and biogas are also used. In diesel engine cogeneration applications, the use of heavy diesel fuel and natural gas is widespread regarding low cost and easy availability [3].

Natural gas is a mixture of components, consisting mainly of methane that compound of 60-90 % with small amounts of other hydrocarbon fuel components. Natural gas contains various amounts of N_2, CO_2, He, and traces of other gases. It is sulfur content ranges from very little to a more significant amount. It is stored as compressed natural gas (CNG) at the pressure of 16 to 25 MPa, or as liquid natural gas (LNG) at the pressure of 70 to 210 kPa and a temperature around – 160ºC. As a fuel, it works best in an engine system with a single throttle body fuel injector. This method provides a longer mixing time required for natural gas. The researchers are performing investigations and development studies on the use of CNG in different sizes of engines. Natural gas is more advantageous as fuel.
Some of these are; the high octane number (around 120) of natural gas makes a proper gasoline engine fuel. For this reason, the high compression ratio can be used in natural gas engines. It has less hydrocarbon and CO_2 emissions than conventional fossil fuels. There are many in the whole world. Natural gas can also be produced from coal, but in this case, it will be more expensive. Dual-fuel diesel engines with natural gas and diesel fuels are developed for truck and stationary applications. The use of natural gas engines is commonly used due to economic reasons and environmental concerns. Natural gas is much cheaper than diesel fuel regarding energy prices. Thus, it is desirable compared to other fuels. Also, natural gas has lower combustion temperatures than diesel fuel, and the temperature can be further reduced by late fuel injection. This dramatically reduces the production of NOx emissions. Thus, because of the lower carbon content in the fuel, less CO2 emissions, and deficient amounts of solid particulate matter, emissions are released [4].

Some literature surveys about the study are given as follows. Kuyumcu et al. [5] performed a performance of a swimming pool heating system by utilizing waste energy rejected from an ice rink with an energy storage tank. Their system consisted of an ice rink, a swimming pool, a spherical underground TES tank, a chiller, and a heat pump. They modeled a computational model in MATLAB program based on the transient heat transfer is used to obtain the annual variation of the ice rink and the swimming pool energy requirements. Yuksel and Goza [6] investigated an economic analysis of a cogeneration facility that is being thought to be built in a 109-bed capacity private hospital that occupies a 22.000 m2 of covered area in Istanbul. The motor drive selected considering the working conditions of the system. Among the three different motor types that were found, it was stated that the motor that has 800 kW power would work more efficiently. It was also noted that the closed cogeneration system amortized itself at the end of 2 years, and the next coming 15 years, it generated 10 million TL profit. Abusoglu et al. [7] presented a thermoeconomic analysis of a biogas engine powered cogeneration system. The operation of an existing cogeneration system was described in detail, and a methodology based on exergoeconomic relations and SPECO method was provided to allocate cost flows through subcomponents of the plant. According to their analyses, the exergetic efficiency of the cogeneration plant was found to be 26.6%, which indicated that 73.4% of the total exergy input to the plant, mainly by biogas, was destroyed. The exergetic cost rate and the specific unit exergetic cost of the power produced in the cogeneration system was calculated to be 90.0 $/h and 25 $/GJ, respectively. Abusoglu and Kanoglu [8] investigated an emission characteristics analysis of diesel engine powered cogeneration. The results showed that using separate units of power and heat production increase the fuel consumption by 34.8% for existing DEPC plant and the DEPC plant can reduce NOx, CO2, and SO2 emissions by 87.6%, 50%, and 41.3%, respectively. Teksan et al. [9] investigated mainly established in Turkey and is still actively continuing to use the installation of cogeneration plants, energy production, efficiency, and technical infrastructure. In this study, it was researched to satisfy the energy requirements of hospitals in forms of electricity and heat with cogeneration systems and to increase efficiency. Colpan [10] presented a thesis about the exergy analysis of a combined cycle cogeneration system. Researcher thesis, several configurations of combined cycle cogeneration systems proposed by the author and an existing system, the Bilkent Combined Cycle Cogeneration Plant, were investigated by energy, exergy, and thermoeconomic

analyses. Yilmaz [11] performed a thermodynamic and economic investigation of a geothermal powered absorption cooling system for buildings. According to the researcher, the energy cost of unit cooling was found to be 0.01295 $/kWh. Boydak et al. [12] investigated an organic Rankine cycle system for the industrial waste heat as the focus is on the waste heat recovery application. The organic Rankine cycle was recognized as an applicable technology to transform low-temperature heat into electricity. It was emphasized in the study that the thermal efficiency of the system was between 10% and 20%, depending on temperature levels and availability of a valid fluid. Unal et al. [13] carried out an experimental performance of a solar-assisted vertical ground source heat pump system for the winter climatic conditions of Mardin, which is in the South-Eastern Anatolia region of Turkey. The energy efficiency, exergy efficiency, and exergoeconomic factors of the entire system were 67.36 %, 27.40 %, and 60.51 %, respectively.

The technical advantages of cogeneration lead to significant energy savings and corresponding environmental advantages. That is, the increase in efficiency and the corresponding decrease in fuel use by a cogeneration system, compared to other conventional processes for thermal and electrical energy production, usually yield significant reductions in energy use and greenhouse gas emissions. These reductions can be as significant as 50 percent in some situations, while the same thermal and electrical services are provided. In this study, the exergy and exergoeconomic analysis of a cogeneration system was conducted, which is planned to be established for a sports complex with a 1000 m^2 area in Afyonkarahisar city. The exergoeconomic cost approximation method integrated from the thermoeconomic isolation method and is applied for a sports complex cogeneration system operating with refrigerant R-410a powered by a natural gas-fueled diesel engine. The use of this exergoeconomic approach requires exergy, and exergoeconomic analysis results. The exergoeconomic procedure of the cogeneration system is described. The method is used for obtaining unit heating and cooling costs exergy efficiencies and related performance parameters for a component isolated from the remaining system components. The system has a dual purpose, refrigerant an ice rink and heating a swimming pool. The unit cost of exergy of these two forms of outputs and the unit cost of energy delivered to the swimming pool is to be investigated.

II. SYSTEM DESCRIPTION AND OPERATING CONDITION OF COGENERATION PLANT

The ideal system configuration of the sports complex is given in Fig.1. The natural gas-fueled cogeneration system is to be installed at a new sports complex to provide both cooling to an ice rink and heating to a swimming pool. It is estimated that the refrigeration duty necessary to keep at - 10ºC is 53.64 kW while the required water temperature of the swimming pool is 30ºC. The R-410a refrigerant plant is selected will operate on an actual vapor-compression refrigeration cycle between the pressure of 100 kPa in the evaporator and 800 kPa in the condenser. The compressor may be assumed to be adiabatic with an isentropic efficiency of 85%. It is driven by a natural gas diesel engine with a power capacity of 53.64 kW. Pressure losses in the heat exchangers and finite heat transfer may be considered negligible. Natural gas-fueled diesel internal combustion engine is used to produce power and heat energy. The electrical power of the cogeneration system is supplied from the natural gas internal combustion engine. Produced power is used for cooling the building in the refrigeration cycle. Engine exhaust gas is supplied from an external source of heating in the building for the heating unit. The refrigeration cycle work is supplied from the natural gas engine. The most critical parameter in a cogenerating heating and cooling units of the buildings is compressor work and heat requirements. The second part of this model is the thermoelectric power generation unit. The natural gas is first burned to an internal combustion diesel engine and then passed through the first part of the system for building the heating unit. The exhaust stream to be powered continues through the other heat exchangers and is finally expanded through an exhaust exchanger to the environment. The thermoelectric power unit is fueled system auxiliary components power requirements (fan and parasitic work consumptions of the system). Actual system operating conditions with state numbers and equipment details are given in Fig. 2.
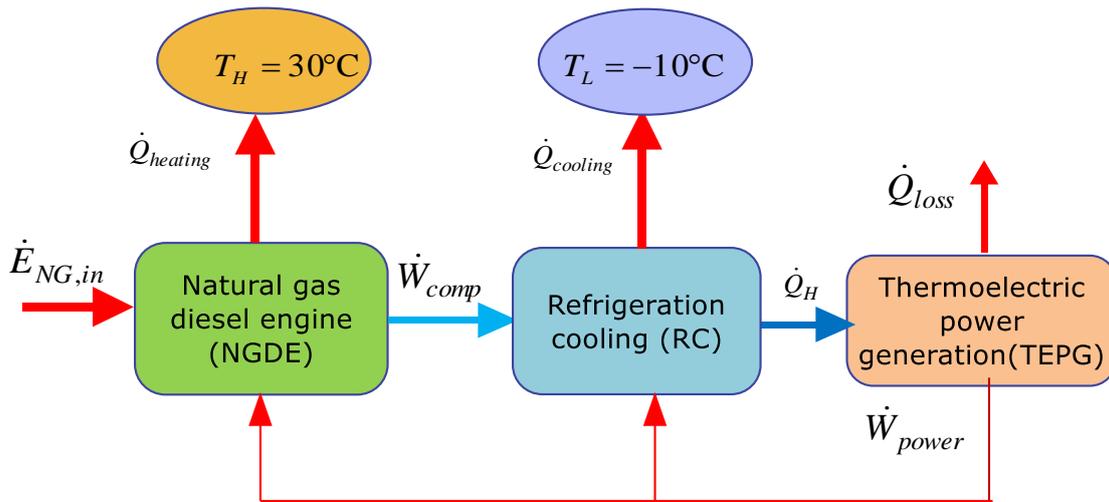
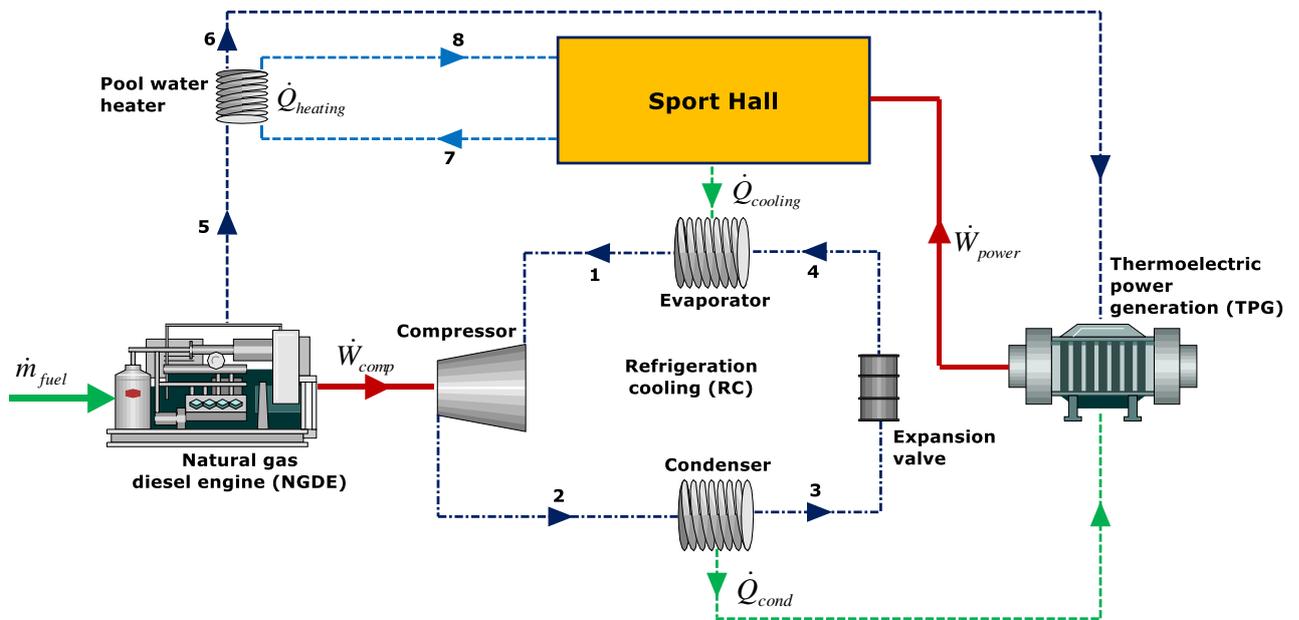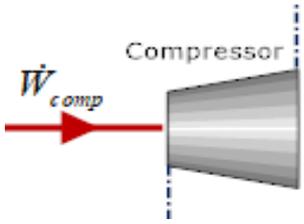*Figure 1*. *Ideal system configuration of sport complex cogeneration system*
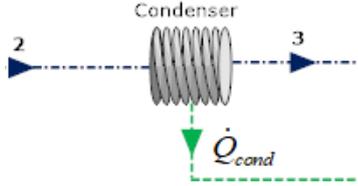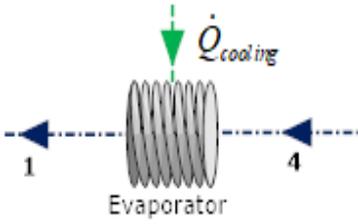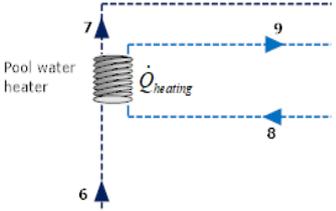

Figure 2. *Actual system of sport complex cogeneration system is operating with a refrigeration cycle powered by natural gas fueled engine*

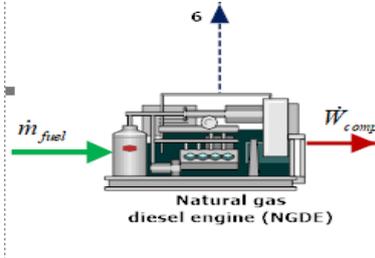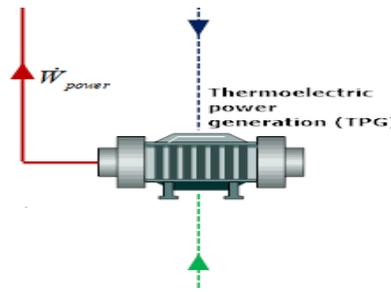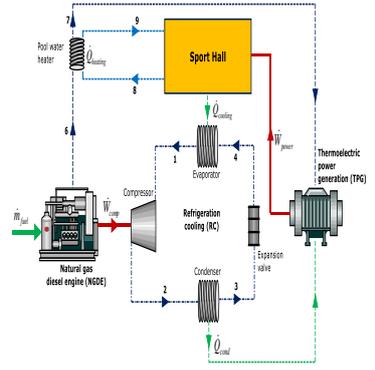# III. ENERGY AND EXERGY RELATIONS OF COGENERATION PLANT

The following assumptions were made for the thermodynamic analysis of the cogeneration system. When the models are considered thermodynamically, each of the system components can be examined by accepting the control volume. All the system and system components were examined in a steady-state and control volume. Kinetic and potential energies have been neglected. For the dead state, the

ambient temperature and pressure are considered as standard assumptions 25ºC and 100 kPa. Thus, the mass, energy, and exergy equations can be written for each system equipment, as in Table 1.

Table 1. *Energetic and exergetic relations for the subsystems of cogeneration plant* [14]

Compressor	$\dot{m}_1 = \dot{m}_2 = \dot{m}_{air}$
	$\dot{W}_{comp,act} = \dot{m}_1(h_2 - h_1)$
	$\dot{W}_{comp,rev} = \dot{m}_1(\psi_2 - \psi_1)$
	$\dot{Ex}_{comp,dest} = \dot{W}_{comp,act} - \dot{W}_{comp,rev}$
	$\eta_{comp} = \dfrac{w_s}{w_{act}} = \dfrac{h_{e,s} - h_i}{h_{e,a} - h_i}$
	$\varepsilon_{comp} = \dfrac{\dot{W}_{comp,rev}}{\dot{W}_{comp,act}} = \dfrac{[h_e - h_i - T_0(s_e - s_i)]}{(h_e - h_i)}$
Condenser	$\dot{Q}_{cond} = \dot{m}_1(h_3 - h_2)$
	$\dot{Ex}_{cond,dest} = T_0\left[\dot{m}_1(s_3 - s_2) + \dfrac{\dot{Q}_H}{T_H}\right]$
	$\varepsilon_{cond} = \dfrac{\dot{Ex}_P}{\dot{Ex}_F} = \dfrac{\dot{Ex}_{\dot{Q}_{cond}}}{\dot{Ex}_2 - \dot{Ex}_3}$
	$\varepsilon_{cond} = \dfrac{\left[\dot{Q}_{cond}\left(1 - \dfrac{T_0}{T_H}\right)\right]}{[\dot{m}_2(h_2 - h_3 - T_0(s_2 - s_3))]}$
Evaporator	$\dot{Q}_{cool} = \dot{m}_1(h_1 - h_4)$
	$\dot{Ex}_{evap,dest} = T_0\left[\dot{m}_1(s_1 - s_4) - \dfrac{\dot{Q}_{cool}}{T_L}\right]$
	$\varepsilon_{evap} = \dfrac{\dot{Ex}_P}{\dot{Ex}_F} = \dfrac{\dot{Ex}_{\dot{Q}_{cool}}}{\dot{Ex}_4 - \dot{Ex}_1}$
	$\varepsilon_{cond} = \dfrac{\left[\dot{Q}_{cool}\left(\dfrac{(T_0 - T_L)}{T_H}\right)\right]}{[\dot{m}_2(h_4 - h_1 - T_0(s_4 - s_1))]}$
Heat Exchanger **Pool Water Heater**	$\dot{Q}_{PWH} = \dot{m}_{water} c_p(T_9 - T_8)$
	$\dot{Q}_{PWH} = \dot{m}_{exh} c_p(T_6 - T_7)$
	$\varepsilon_{PWH} = \dfrac{\dot{m}_8(\psi_9 - \psi_8)}{\dot{m}_6(\psi_6 - \psi_7)}$
	$\dot{Ex}_{PWH,dest} = \dot{m}_6(\psi_6 - \psi_7) - \dot{m}_8(\psi_9 - \psi_8)$

Table 1. *(continuation) Energetic and exergetic relations for the subsystems of cogeneration plant* [14]

Natural Gas Diesel Engine Natural gas diesel engine (NGDE)	$\dot{Q}_{in} = \dot{m}_{fuel}(q_{LHV})\eta_{comb}$ $\eta_{comb}=0{,}98$ $\dot{n}=2000$ rpm $m=m_{fuel}+m_{air}$ $\dot{m}_{exhaust,total}= (\dot{m}_{fuel}+\dot{m}_{air})4$ $\dot{m}_{fuel} = m_{fuel}(\dot{n}/60)0.5$ $\dot{m}_{fuel,total}= \dot{m}_{fuel}.4$ $\dot{Q}_{out} = \dot{m}_{water}c_p(T_4 - T_1)$ $\dot{W}_{net,out} = \dot{Q}_{in} - \dot{Q}_{out}$ $\eta_{th} = \dfrac{\dot{W}_{net,out}}{\dot{Q}_{in}}$
Thermoelectric Generator	$\eta_{TPG}=0.02$ $\dot{Q}_{waste} = \dot{m}_{exh}c_p(T_{exh} - T_0)$ $\dot{W}_{TPG} = \eta_{TPG}(\dot{Q}_{waste} + \dot{Q}_{cond})$
Cogeneration Cooling System	$\Psi_{NG}=51{,}978$ kJ/kg $\dot{Ex}_{in,plant} = \dot{m}_{fuel}\psi_{NG}$ $\dot{Ex}_{\dot{Q}_{cool}} = \dot{Q}_{cool}\left[\dfrac{T_0 - T_L}{T_H}\right]$ $\dot{Ex}_{\dot{Q}_{heating}} = \dot{Q}_{PWH}\left[\dfrac{T_H - T_0}{T_H}\right]$ $\varepsilon_{plant} = \dfrac{\dot{W}_{TPG} + \dot{Ex}_{\dot{Q}_{cool}} + \dot{Ex}_{\dot{Q}_{heating}}}{\dot{Ex}_{in,plant}}$

IV. THERMODYNAMIC PERFORMANCE PARAMETERS OF COGENERATION PLANT

Thermodynamic modeling of the components of the cogeneration system using different means of cooling has been carried out and the governing equations to predict its performance are developed accordingly. The cogeneration system performance parameters include η_{cog}, ε_{cog}, and η_{NGDE}, which are expressed as follows [15]:

$$\eta_{cog} = \frac{\dot{Q}_{process} + \dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{m}_{water}\Delta h + \dot{W}_{net}}{\dot{m}_{fuel}q_{LHV}} \tag{1}$$

$$\varepsilon_{cog} = \frac{\dot{Ex}_{process} + \dot{W}_{net}}{\dot{Ex}_{in}} = \frac{\dot{m}_{water}[h_e - h_i - T_0(s_e - s_i)] + \dot{W}_{net}}{\dot{m}_{fuel}\psi_{LHV}} \tag{2}$$

$$\eta_{NGDE} = \frac{\dot{W}_{net}}{\dot{m}_{fuel}q_{LHV}} \tag{3}$$

where $\dot{Q}_{process}$ represents the heat rejected to the pool water heating process in the natural gas diesel engine exhaust gas, $\dot{Q}_{in}$ is the rate of heat input to the plant, $\dot{m}_{fuel}$ is the mass flow rate of natural gas fuel and q_{LHV} is the heatin g value of natural gas, $\dot{W}_{net}$ is the net work output to the system, and ψ_{LHV} is the specific exergy of the natural gas fuel.

V. EXERGOECONOMIC ANALYSIS OF COGENERATION PLANT

Exergoeconomic is an essential system performance evaluation method based on thermodynamic and economic analysis. It shows us not only the engineering feasibility of a system but also its feasibility in terms of economically. For this purpose, after a detailed energy and exergy analysis, a combined analysis is made by taking into account the required investment parameters. Excellent results and determinations can be obtained for a system by combining these values. Also, this method supplies to cost assignment of all streams and equipment, both at the overall system and at the equipment level. This allows you to track the cost of any equipment and flow stream in an engineering system. This provides a great advantage for detecting and improving both thermodynamic and costs losses in the system. With thermoeconomic analysis, cost optimization of the system can be performed, and energy losses can be minimized. Nowadays, thermodynamic analysis is not sufficient in energy system projects. Because of the economic feasibility, product unit cost analysis, and necessary optimization of the system are also required. An engineering study without these is very weak. Because engineering projects, especially in the scope of energy, are costly investments and it is very important to prevent a small loss [16].

Considering the thermodynamic and economic structure of the cogeneration system, the basic exergetic cost equations expressing the relations of exergy and cost can be written for each form of energy as follows:

$$\dot{C}_i = c_i \dot{Ex}_i = c_i(\dot{m}_i\psi_i) \tag{5}$$

$$\dot{C}_e = c_e \dot{Ex}_e = c_e(\dot{m}_e\psi_e) \tag{6}$$

$$\dot{C}_w = c_w \dot{W} \tag{7}$$

$$\dot{C}_q = c_q \dot{Ex}_q \tag{8}$$

According to these definitions, for a system component with all thermodynamic interactions, the general exergetic cost balance equation can be written as follows:

$$\sum_e \left(c_e \dot{E}x_e \right)_k + c_{w,k} \dot{W}_k = c_{q,k} \dot{E}x_{q,k} + \sum_i \left(c_i \dot{E}x_i \right)_k + \dot{Z}_k \qquad (9)$$

where c_i, c_e, c_w and c_q denote average costs per unit of exergy in dollars per gigajoule ($/GJ). A cost balance applied to the k_{th} system component shows that the sum of cost rates associated with all exiting exergy streams equals the sum of cost rates of all entering exergy streams plus the appropriate charges due to capital investment and operating and maintenance expenses. The sum of last two terms is denoted by $\dot{Z}_k$. Table 2 shows the purchase equipment cost values and the $\dot{Z}_k$ values based on system lifetime of the plant. $\dot{Z}_k$ parameter is denoted by the capital investment cost rate. In this study, basic economic assumptions were taken from the Aspen Plus software which is a current economic analysis program. Based on these costs, the overall relations for the cost ratio associated with initial investment and maintenance costs for any system component can be expressed as follows [17, 18]:

$$\dot{Z}_k = \frac{C_k (CRF)}{t_{op}} \qquad (10)$$

here C_k is the initial investment cost of the equipment ($) and t_{op} is the annual operating time of the system (7800 h). The purchased equipment component costs are calculated using the economic analysis database of Aspen Plus software. The capital recovery factor (CRF) depends on the interest rate as well as estimated equipment life time. Depending on the interest rate ($i = 10\%$) and system life ($N = 20$ years), this value can be expressed as follows [17, 18]:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (11)$$

In this study, considering the 10% interest rate and 20 years of system lifetime, CRF value was calculated as 0.1175. Table 2 was expressed based on *CRF* value and equipment purchase costs. Detailed cost analysis results of the system and the system equipment are given in Table 2.

Table 2. *The cost rates associated with the components of the plant* [17, 18].

System components	C_k ($)	$\dot{Z}_k$ ($/s)
Natural Gas Diesel Engine	25,000	0.0001046
Compressor	15,000	0.00006275
Condenser	5,000	0.00002092
Expansion Valve	2,000	0.000008366
Evaporator	5,000	0.00002092
Pool Water Heater	5,000	0.00002092
Thermoelectric Generator	5,000	0.00002092
Total purchase equipment cost (PEC)	62,000	-
Operating and maintenance cost (OMC)	5,000	-

Exergetic cost relations for the natural gas-powered cogeneration system are given in Table 3. Mathematically, there are n numbers of unknown equal to the sum of the exergy flows from all sub-components of the system, and the cost equilibrium equation alone is not sufficient to calculate these n numbers of unknown. Therefore, one missing (n-1) auxiliary equation must be defined from the number of unknowns. In our study, taking into account the specific exergy cost method (SPECO), a sufficient number of auxiliary equations have been developed for each system component with the help of exergy Fuel and Product principles. These equations and the exergy-dependent cost balance

equation are given in Table 3 for the system. Technical assumptions were made, and auxiliary equations were written and solved by coding in the EES program on a computer.

Table 3. Exergetic cost relations for the natural gas powered cogeneration system

Components	Exergetic cost balance equations	Auxiliary Equations
Natural Gas Diesel Engine	$c_f \dot{E}x_{in} + \dot{Z}_{NGDE} = c_{elec} \dot{W}_{net} + c_6 \dot{E}x_6$	c_{elec} (variable) c_f (known)
Compressor	$c_{elec} \dot{W}_{net} + \dot{Z}_{Comp} + c_1 \dot{E}x_1 = c_2 \dot{E}x_2$	c_1 (known) c_2 (variable)
Condenser	$c_2 \dot{E}x_2 + \dot{Z}_{Cond} = c_{cond} \dot{E}x_{Cond} + c_3 \dot{E}x_3$	c_{cond} (variable)
Expansion Valve	$c_3 \dot{E}x_3 + \dot{Z}_{EV} = c_4 \dot{E}x_4$	$c_6 = c_4$
Evaporator	$c_4 \dot{E}x_4 + \dot{Z}_{Evap} + c_{Cool} \dot{E}x_{Evap} = c_1 \dot{E}x_1$	$c_{cooling}$ (variable)
Pool Water Heater	$c_5 \dot{E}x_5 + \dot{Z}_{PWH} + c_7 \dot{E}x_7 = c_6 \dot{E}x_6 + c_8 \dot{E}x_8$	$c_5 = 0$ c_8 (variable)
Thermoelectric Generator	$c_{elec} \dot{W}_{Power} = \dot{Z}_{TPG} + c_6 \dot{E}x_6 + c_{cond} \dot{E}x_{Cond}$	c_6 (known)

Thus, cost loss due to exergy destruction can also be calculated in the sub-components of the system, which will play a very important role in shaping the cost structure of the system. In exergoeconomic analysis studies, the cost performance of a system subcomponent varies depending on both the sum of initial investment and operating and maintenance costs, and the exergy destruction cost of the system.

VI. RESULTS AND DISCUSSION

In this study, a diesel engine with natural gas support provides energy to the system in order to provide the heating and cooling required by the sports complex. Taking into account the approximate energy requirement of the sports complex, the power of the diesel engine was calculated as 53.64 kW. The electricity produced from the natural gas diesel engine is used in the drive of the compressor in the vapor compression refrigeration cycle to provide the required -10°C temperature for the ice rink. The high-temperature exhaust gases of the engine were sent to the heat recovery unit and used in the sports complex to provide hot water at the required 30°C temperature for the pool. Accordingly, a four-cylinder diesel engine with a compression ratio of 17 and operating at 2000 rpm was thermodynamically analyzed by real air standard assumptions. As a result of the analysis, the natural gas consumption of the diesel engine used to provide the required 53.64 kW power was calculated as 0.002383 kg/s. The thermal efficiency of the diesel engine was found to be 52.21% according to these values. The swimming pool referred to the system in Fig. 2 is to be provided with pool water heater from the natural gas-fueled diesel engine exhaust gas with a nominal output 53.64 kW and combustion efficiency of 98% based on the calorific value of the natural gas 50,000 kJ/kg. The chemical exergy of the gas is 51,978 kJ/kg. Assuming the unit exergetic cost of the natural gas-based on its net calorific value to be 0.014 \$/kWh (3.89×10^{-6} \$/kJ). With this pool water heater exchanger, it is possible to produce hot water to be used for various purposes in the sports complex at a flow rate of 0.1906 kg/s at a temperature of 90°C. Finally, exhaust gases falling to 382°C are sent to an ideal thermoelectric power generation and used in electricity generation in order to supply the parasitic work consumption of the system. This thermoelectric unit is also supported by the waste heat energy $\dot{Q}_H$ from the refrigeration cycle condenser operating with R410a. Thus, the actual usable work that can be produced from the thermoelectric unit is calculated as 3.885 kW. The produced work of 53.64 kW from the natural gas engine will be sent to the cooling unit using vapor compression with R410a working fluid to supply the cooling requirements of the system. Considering the requirements of the sports complex (cooling and ice rink), this energy amount $\dot{Q}_L$ was calculated as 119.4 kW. The heat discharged from the condenser $\dot{Q}_H$ is 173 kW. The refrigerant

working fluid flow rate of the cooling system is 0.8994 kg/s. This will provide the sports complex with a temperature of -10°C for the required ice rink area. When the actual thermodynamic analysis of the cooling system is performed, the COP value is calculated as 2.225.

When the exergy analysis was performed through the energy analysis of the study, the net exergy input into the system was calculated as 123.9 kW considering the values of natural gas. When this exergy is converted to heating and cooling work potentials, cooling exergy $\dot{Ex}_{\dot{Q}_L}$ is calculated as 15.82 kW, and heating exergy $\dot{Ex}_{\dot{Q}_H}$ is calculated as 15.89 kW. According to Eq. 10, the overall exergy efficiency of the natural gas cogeneration sports complex is 28.74%. Another important issue here is the exergy loss potential of the system equipment. Exergy destruction for all system equipment is calculated, taking into account Table 1 and are shown in Figure 3. Accordingly, the most destructive component is the natural gas diesel engine with 70.21 kW. This value is high due to the irreversibility of combustion reactions and the low potential for conversion to useful work. However, the most destructive component in the refrigeration cycle is the condenser unit with 72.25 kW. This is due to finite temperature differences and heat transfer problems in the exchanger structure. Using this data and assumptions, the following quantities were evaluated in Table 4.

Table 4. Energy and exergy analyses results of the cogeneration plant

| Component	$\dot{Q}$ (kW)	$\dot{W}$ (kW)	$\dot{Ex}_F$ (kW)	$\dot{Ex}_P$ (kW)	$\dot{Ex}_{dest}$ (kW)	ε (%)
Natural Gas Diesel Engine	116.8	53.64	123.9	53.64	70.21	43.31
Compressor	-	53.64	53.64	46.15	7.497	86.2
Condenser	173	-	122.4	50.14	72.25	40.97
Expansion Valve	-	-	106.6	35.95	70.61	33.74
Evaporator	119.4	-	35.95	19.88	16.07	55.29
Pool Water Heater	55.8	-	41.85	4.955	36.9	11.84
Thermoelectric Generator	194.24	3.885	22.63	3.885	18.74	17.17
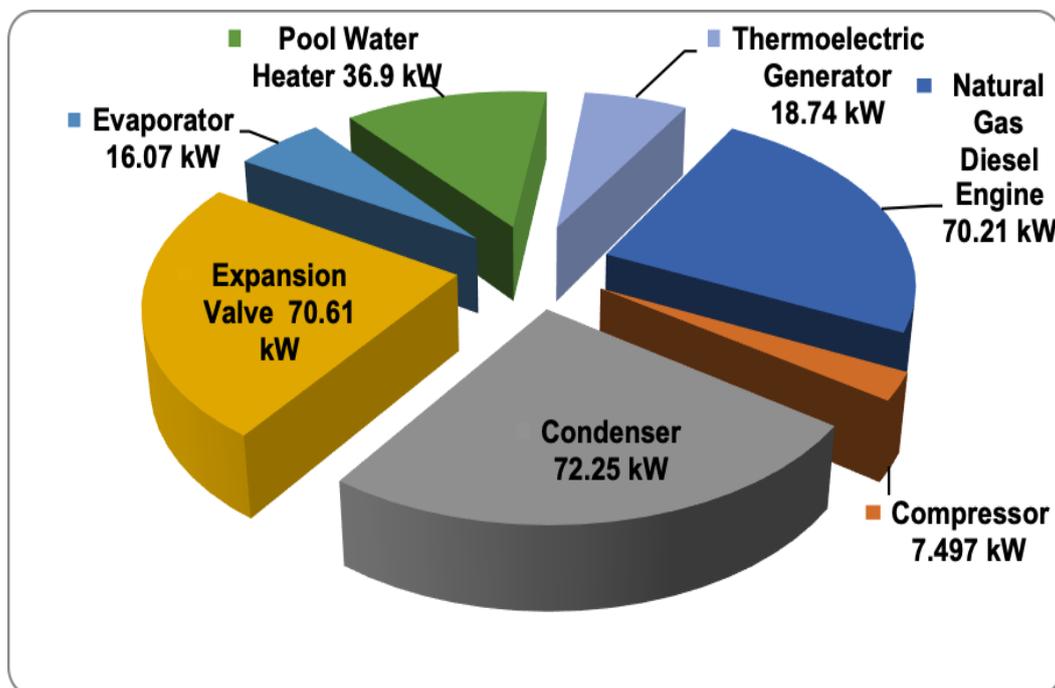
Figure 3. Exergy destructions in the components of the plant

The exergoeconomic analysis of the system was carried out using the equations in section 5, taking into consideration 7800 hours of operation time per year, 10% interest rate, and 20 years of system lifetime. Here it is possible to find the costs of system equipment from the literature or using many cost analysis programs. In our study, we found the approximate costs according to the capacity of the system equipment by coding the system to the Aspen Plus program. The total initial investment cost of the system was found to be $ 62,000. Accordingly, when necessary cost equations (Table 3) are coded into the EES program and solved simultaneously, the exergetic cost of each equipment can be calculated as $/GJ. The most important parameters in this study are the cost of electricity generated, ice rink cooling cost, and swimming pool heating cost. The unit exergetic cost of electricity generated from the cogeneration system is calculated as 10.93 $/GJ. In other words, the cost of unit electricity is 0.039 $/kWh. The exergetic cost required for cooling the ice rink in the sports complex was found to be 6.152 $/GJ or 0.022 $/kWh. Finally, the unit exergetic cost of the water to be used in the swimming pool heating was calculated as 4.221 $/GJ or 0.0152 $/kWh. As can be seen, these values are considerably lower than the unit cost of electricity that will be generated by using direct electricity, which is 0.08 $ / kWh. This shows that the design of natural gas-assisted cogeneration sports complex is a very attractive and reasonable investment. This advantage is also important because of the cost and environmental impact of natural gas. The use of natural gas in this system can provide a great advantage in terms of both cost and emissions. Also, detailed exergetic cost values calculated for all system states and equipment are given in Table 5.

Table 5. *Thermoeconomic results associated with each stream of the plant*

State	$\dot{Ex}$ (kW)	C ($/GJ)	$\dot{C}$ ($/h)
1	3.99	28.67	0.4118
2	50.14	15.23	2.749
3	106.6	0.1185	0.04545
4	35.95	0.1185	0.01533
5	48.65	0	0
6	6.802	3.495	0.0856
7	0	0	0
8	4.955	4.221	0.07529
$\dot{W}_{NGDE}$	53.63	3.89	0.7512
$\dot{W}_{Comp}$	53.64	10.93	2.111
$\dot{W}_{TPG}$	3.885	10.93	0.1529
$\dot{Q}_{Heating}$	55.8	4.221	0.07756
$\dot{Q}_{Cooling}$	119.4	6.152	0.3518

Distribution of exergetic cost destruction rate ($/h) of the cogeneration plant equipment is given in Fig. 4. The condenser heat exchanger is the higher exergy cost destructive component compared to the other plant components. The way of reducing the cost of cooling generated in the cogeneration plant is to reduce the exergy cost destruction of the system. In order to reduce the exergetic cost of cooling and heating productions, it is also considered to increase system efficiency, to reduce exergy losses and to optimize operating conditions of the plant.
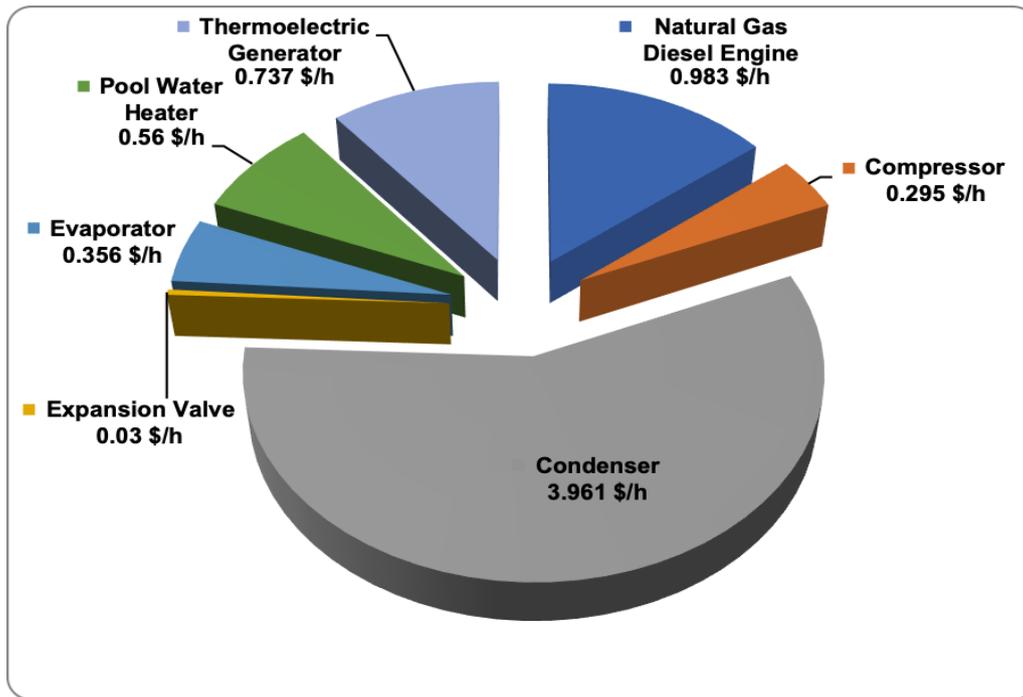
Figure 4. *Distribution of exergetic cost destruction rate diagram of the system parts*

VII. CONCLUSIONS

An exergy and exergoeconomic analysis of natural gas-fueled diesel engine powered sports complex cogeneration system was presented about the proposed use of these fuels as alternatives to satisfy the requirements of cooling of all areas. The results of this study can be used to improve the process flows and reduce product costs.

- The integrated use of natural gas in heating and cooling systems can be considered as a viable alternative in terms of sustainable energy technology, and the system proposed in this study is an excellent example of such an application. Also, the unit cost of electricity generated in the natural gas-assisted cogeneration cooling system is calculated as 0.039 $ /kWh. Considering the analyses results of the designed cogeneration-supported sports complex (which is much lower than the unit cost of grid electricity of 0.08 $/kWh), the design is a very attractive and reasonable investment, and the use of natural gas in the system provides a great advantage in terms of both cost and emissions.

- As will be seen from the above results, the sports complex cogeneration plant has both higher energy and exergy efficiencies and is capable of delivering heating of the swimming pool at about double the cost of that of the conventional water heater.

- The low interest rate provides the use of more expensive equipment, which helps to higher the exergy efficiency of the system. However, when the unit cost of input exergy increases, it is necessary to use a more expensive system, resulting in higher operational efficiency to achieve the lowest unit cost in the system outputs.

- Environmental emissions can be reduced by increasing conservation efforts and improving energy conversion efficiencies while meeting new energy demands by the use of the cogeneration system. Carbon dioxide and other emissions can be reduced significantly by the use of natural gas diesel engines for the heating and cooling processes of industrial applications.

Therefore, considering the whole system in terms of emissions, this cogeneration system will result in a significant emission reduction because the emissions required for a sports complex operating at the same capacity (electricity, heating, and cooling) will be reduced.

VIII. NOMENCLATURE

c	Cost per unit of exergy ($/GJ)
C	equipment purchased equipment cost ($)
$\dot{C}$	Cost rate associated with exergy ($/h)
CRF	capital recovery factor
$\dot{Ex}$	Exergy rate (kW)
h	Enthalpy (Kj/kg)
i	interest rate (%)
$\dot{m}$	Mass flow rate(kg/s)
N	Time period (year)
NGDE	natural gas diesel engine
OMC	Operating and maintenance costs ($/yr)
PEC	Purchased equipment cost ($)
$\dot{n}$	engine cycle (rpm)
$\dot{Q}$	heat flow rate (kW)
T	Temperature (ºC)
$\dot{W}$	power rate (kW)
$\dot{Z}$	Cost rate associated with capital and O&M expenses($/h)

Greek Symbols

η	energy efficiency
ε	exergy eefficiency
Ψ	Specific flow exergy (kJ/kg)

Subscripts

0	dead states
act	actual
cond	condenser
comp	compressor
dest	destruction
e	exit state
exh	exhaust
evap	evaporator
g	gas
i	inlet state
k	k-th component
LHV	lower heating value
PHW	pool water heater
rev	reversible
s	isentropic
th	thermal
TPG	thermoelectric power generation

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