REVIEW

Thermodynamic and economic analysis of performance evaluation of all the thermal power plants: A review

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Abstract

Surging in energy demand makes it necessary to improve performance of plant equipment and optimize operation of thermal power plants. Inasmuch as thermal power plants depend on fossil fuels, their optimization can be challenging due to the environmental issues which must be considered. Nowadays, the vast majority of power plants are designed based on energetic performance obtained from first law of thermodynamic. In some cases, energy balance of a system is not appropriate tool to diagnose malfunctions of the system. Exergy analysis is a powerful method for determining the losses existing in a system. Since exergy analysis can evaluate quality of the energy, it enables designers to make intricate thermodynamic systems operates more efficiently. These days, power plant optimization based on economic criteria is a critical problem because of their complex structure. In this study, a comprehensive analysis including energy, exergy, economic (3-E) analyses, and their applications related to various thermal power plants are reviewed and scrutinized.

KEYWORDS
cogeneration system, combined cycle, economic analysis, energy analysis, exergy analysis

1 | INTRODUCTION

Increase in energy use is inevitable in developing stages of countries and is necessary to achieve higher quality of living. Various parameters cause energy use growth including industrialization, urbanization, and surging in population. Energy use increase leads to several environmental problems.[1,2] Several studies have focused on more environmentally benign energy systems to reduce greenhouse gas emissions.[3-5]

Different aspects of life depend on energy such as agriculture, industry, transport etc. Approximately 80% of power generation of world is provided by fossil fuels and the remaining part works with other types of energy sources such as nuclear energy or renewable energies sources.[6-9] Typically, thermal power plants are assessed by applying energetic performance which obtained from first law of thermodynamic.[10] Another criterion for evaluation energy system is exergetic performance which is based on second law of thermodynamics.[11-13] Exergetic performance is an appropriate method for design, assessment, and optimizing thermal power plants. Causes and reasons of irreversibilities in a system can be distinguished by exergetic analysis and get better insight into efficiency of each part of the system. The mentioned characteristics of the exergy performance analysis make it different from energetic performance analysis. Attributed to this fact, utilizing both energetic and exergetic analysis gives designers a significant insight into the system. This type of analysis enables designers to have more appropriate method to assess and determine the steps toward enhancement.[14-18]

J. Willard Gibbs developed the concept of exergy. More development continued by Zoran Rant later. H. D. Baehr, defined exergy as the part of energy converted into all other forms of energy. Exergy concept is defined based on second law of thermodynamic and irreversibilities due to entropy generation.[19-23]

It is possible to find losses occur in systems by using exergy analysis.[24] Exergy analysis facilitates obtaining energy conversion at various stages, efficiencies of different parts of system, and points where there are high losses and helps us to reduce losses.[25,26] This method is the most appropriate approach in optimizing cycle by given input data.[27] Exergy analysis and the area of its validity have been also carefully discussed.[28-30] Since it is powerful method in determining energy quality, makes it possible to enhance efficiency of complicated thermodynamic systems. Exergy losses can be divided into two parts: avoidable and inevitable.[31] Distinguishing the type of losses based on the mentioned criterion, facilitate understanding the process. Electrical power generation system development reviewed by Ref.[32] and the special attentions are given to the plant efficiency.

Aljundi[33] evaluated a steam power plant and by a component wise modeling and a detailed break-up of energy and exergy losses. Datta et al[34] investigated a thermal power plant works with coal as fuel and analyzed it based on exergy by dividing the system into three parts.

Zubair and Habib[35] evaluated regenerative-reheat Rankine cycle power plants by applying second law thermodynamic analysis. Second law thermodynamic analysis was performed by Reddy and Butcher[36] to investigate waste heat recovery-based power generation system. Suresh et al[37] obtained exergetic performance of a thermal power plant working with coal as fuel under different steam conditions including ultra-supercritical, supercritical, and subcritical. Oktay[38] determined exergy losses and represented approaches in order to enhance a fluidized power plant. In another study, Reddy et al[39] investigated combined cycle power generation working with natural gas as fuel and analyzed influence of various parameters including pressure ratio and turbine inlet temperature (TIT) on the plant exergetic efficiency. Srinivas et al[40] conducted a study on a combined cycle power plant working with methane and applied the first and second laws of thermodynamics for evaluation. Can et al[41] explained a straightforward and precise approach to approximate directly the Rankine bottoming cycle generated power by using the gas turbine exhaust exergy and applying the second law of thermodynamics.

Taillon et al[42] designed two new graphs for exergy efficiency of thermal power plants. Jiang et al[43] represented a novel approach for promoting power plants. In their analysis, effects of feedwater temperature and secondary air temperature on the boiler and plant were investigated based on exergy analysis theory. Obtained results predicted that surging in the temperature of feedwater can cause higher temperature of secondary air; therefore, the exergy loss in the boiler reduces and plant exergy efficiency enhances.

Datta et al[44] analyzed an externally gas-fired turbine cycle integrated with biomass gasifier used for generating power based on energy and exergy points of view. Sue et al[45] analyzed power generation system working with combustion gas turbine based on exergy concept. Bilgen[46] represented analyses based on exergy and engineering point of view and simulated a cogeneration plant using gas turbine. The plant included both gas and steam turbine and heat recovery system for steam generation. Khaliq et al[47] applied the second-law method to analyze a reheat combined Brayton/Rankine power cycle thermodynamically. Woudstra et al[48] determined the cogeneration process, levels of steam generation in order to decrease exergy loss, which is as a result of the exhaust of flue gas to the stack, in addition to reduction the heat transfer losses occur in the heat recovery steam generator (HRSG).

Cihan et al[49] analyzed a combined cycle, located in turkey, based on exergy and energy. In this study, some moderations were suggested in order to decrease exergy destruction in the plant. Obtained results indicated that the

main sources of irreversibilities were combustion chamber, gas turbines, and heat recovery system utilized for steam generation. This equipment had more than 85% of plant exergy losses.

Barzegar et al[50] conducted exergy environmental evaluation on power plant working with gas turbine. Results indicated improvement in exergy efficiency and reduction in CO_2 emission. Ehyaei et al[51] optimized a micro gas turbine based on exergy, economic, and environmental concepts. The study was conducted for several fuels. Based on results, optimization was little influenced by the type of fuel.

Ahmadi et al[52-54] conducted a study on steam cycle of a power plant with 200 MW capacity. The EES software was applied, and mass, energy, and exergy equations were solved. Results indicated that condenser consumed the highest level of waste, ie 69.8% of the total. In addition, the highest exergy loss occurred in boiler.

Maghsaudi et al investigated a coal fired power plant in order to evaluate its exergy and energy efficiencies. Their results showed that in condenser section, the energy loss is critical while the majority of exergy loss took place in the boiler.[55]

In recent years, researchers focused their studies on 4-E analysis of thermal power plant for energy quality optimization. Several review papers are represented on exergy analysis in order to obtain better insight into related problems.[56] In power plants, insights have been provided into various energy and exergy efficiencies which are helpful for design engineers.[57] Combination of economic and exergy analysis is a powerful tool in order to enhance thermal performance of power plants and devices consuming energy.[58] A novel

approach is represented by Ref.[59] to design power plants facilitating optimal plant based on thermo-economic concepts.

Ganji et al[60] analyzed the apparatuses in heat recovery steam generators (HRSGs) utilized in combined-cycle power plants based on exergy and energy in order to develop an optimization plan. Various parameters were investigated in this study including drum pressure and arrangement of heat exchangers in HRSGs for high and low-pressure components.

In this paper, various studies conducted on coal-fired, natural gas-fired, and combined-cycle power plants as well as cogeneration systems have been reviewed and analyzed using a comprehensive analysis including energy, exergy, economic (3-E) analyses, and their key results are derived and presented.

2 | THREE-E ANALYSES OF POWER PLANTS

2.1 | Coal-fired power plant

2.1.1 | Energy analysis

One of the coal-fired power plants which is owned by Turkey government is selected in this investigation. Zero- dimensional approach is presented to analyze the system from energy and exergy viewpoints. The benefit of utilizing this approach is that it makes the results comparable to each similar power plant. The modeling was performed in a unit by unit procedure. In order to obtain continuous mass flow diagram, information from the plant manager and the results of
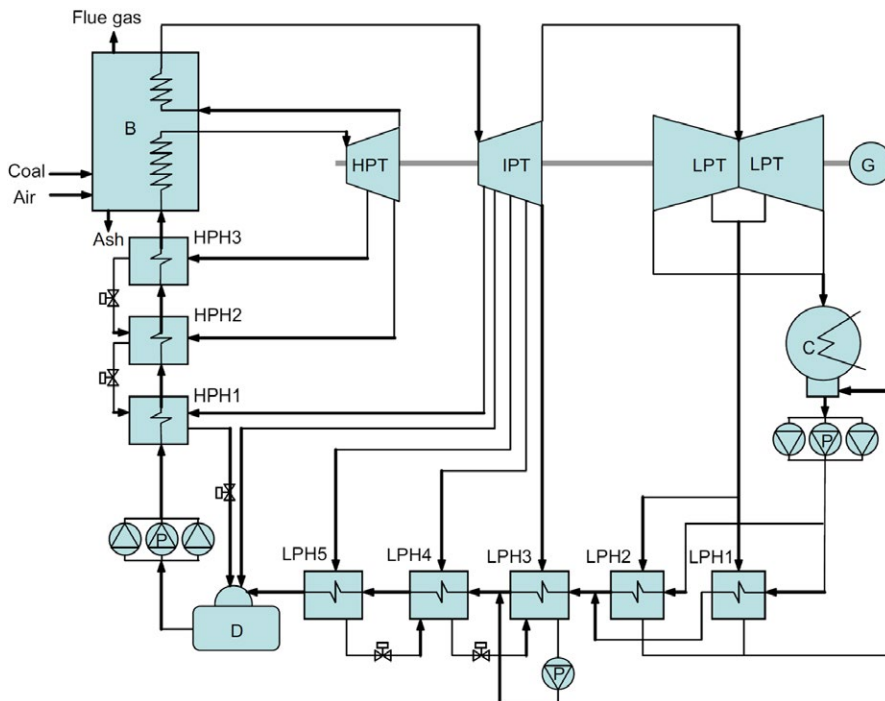

FIGURE 1 A schematic mass flow diagram of a coal-fired thermal power plants[6]

observations via modeling process are applied.[6] As it is illustrated in Figure 1, these obtained diagrams are processed by drawing the mass flow lines in the ceaseless operating condition of the plants. Figure 1 demonstrate that a ceaseless mass flow diagram for each similar power plant throughout this modeling approach consists of some major factors such as turbines in different working pressure statuses including high, intermediate, and low-pressure turbine (HPT, IPT, and LPT, respectively), a boiler (B), various pumps (P), a deareto (D), a generator (G), a condenser (C), low and high-pressure feed water heater groups (LPH and HPH respectively). Mass, energy, and exergy conservation fundamentals are considered to develop the thermodynamic models. Through balance equation solving procedure, any required thermodynamic associated terms such as energy or exergy output flow from the turbine, needed pump work, the required heat of the boiler, energy, or exergy flow at each point of the plant cycle, associated energy or exergy efficiency for each equipment in the plant, irreversibility terms for each device individually and also for the whole power plant, etc. The fundamentals thermodynamic theory of energy and exergy modeling is discussed in further sections. Some assumptions are made in the modeling procedure of the power plant, ie (a) design conditions are regarded for evaluating the performance of the whole power plant; (b) a single control volume is defined for each equipment in the analysis process; (c) all the employed equipment are working on the basis of steady-state thermodynamic conditions; (d) all the gas components in the plant are governed by Ideal gas principles; (e) the variation in kinetic and potential energy and their associated exergy terms are neglected in this study; (f) the defined reference condition are 25°C and 1.013 bar, and (g) it is assumed that there is no temperature difference between the equipment control volumes and their close neighborhoods.

Energy analysis is on the basis of the 1st law of thermodynamics. As it is stated in the 1st law of thermodynamics, the net output work and the associated thermal efficiency are the major performance benchmark. These terms are also critical in case of economic analysis. By employing the corresponding thermodynamic parameters (enthalpy (h), pressure (p), temperature (T), entropy (s), mass flow rate ($\dot{m}$), and quality (x)) over the written balance equation of each equipment, any input or output value can be obtained. For example, the below equation, Equation (1) is derived for calculation of the output work resulted from a steam turbine:

$$\dot{W}_T = \dot{m}_{in}\left(h_{in} - h_1\right) + \left(\dot{m}_{in} - \dot{m}_1\right)\left(h_1 - h_2\right) + \left(\dot{m}_{in} - \dot{m}_1 - \ldots - \dot{m}_n\right)\left(h_n - h_{out}\right) \tag{1}$$

In above equation, the subscripts of 1,2,…n are the stages of steam extraction in the steam turbine. In this analysis, Pump is considered as the only work consuming equipment

in the power plant. The pump power is easily obtained by using the following equation:

$$\dot{W}_P = \frac{\dot{m}\left(h_{out} - h_{in}\right)}{\eta_P} \tag{2}$$

Here, η_P denotes the pump efficiency.

And the total useful electrical output power of the plant is obtained by:

$$\dot{W}_{Net} = \sum \dot{W}_T - \sum \dot{W}_P. \tag{3}$$

The following equation is used in the studied model to calculate the required thermal energy which is supplied by the boiler in the studied power plant:

$$\dot{Q}_B = \frac{\dot{m}_{sh}\left(h_{sh,out} - h_{sh,in}\right) + \dot{m}_{rh}\left(h_{rh,out} - h_{rh,in}\right)}{\eta_B} \tag{4}$$

In above Q_B calculation equation, subscripts sh and rh are representing superheat and reheat conditions respectively. The efficiency of the boiler is shown by η_B. In Equation (4), the boiler inlet enthalpy ($h_{sh,in}$) is not known. Therefore, the energy conservation law should be written around the feed water heater in order to obtain $h_{sh,in}$:

$$\left(\dot{m}_s h_s\right)_{in} + \left(\dot{m}_{fw} h_{fw}\right)_{in} = \left(\dot{m}_s h_s\right)_{out} + \left(\dot{m}_{fw} h_{fw}\right)_{out} \tag{5}$$

s and fw subscripts are steam and feed water respectively. It should be highlighted that as the feed water heaters outlet temperature is unknown at the first step, a similar procedure as Equation (5), a mass-conservation balance, should be performed to calculate the outlet temperature of the feed water heater.

The power plant's thermal efficiency is calculated by utilizing the following equation:

$$\eta_{th} = \frac{\dot{W}_{Net}}{\dot{m}_{coal}LHV}, \tag{6}$$

where the coal lower heating value of coal is represented by LHV and $\dot{m}_{coal}$ is defined as coal feed flow rate into the burner of the boiler, which is calculated as follows:

$$\dot{m}_{coal} = \frac{\dot{Q}_B}{LHV}. \tag{7}$$

2.1.2 | Exergy analysis

Exergy analysis modeling is defined on the basis of the second law of thermodynamics. The resulted outcomes from exergy analysis can be utilized to check and also monitor the irreversibility locations and proposed different methods to

lower it to the possible least irreversibility value by improving the system performance. In other words, exergy stated the transformation potential and a high limitation level for an energy flow or source to achieve the highest theoretical work under a specified environmental conditions which is defined by at least two thermodynamic variables, usually temperature and pressure.[22,61] In this investigation, exergy analysis is carried out to specify exergy efficiency and also exergy destruction rate of each equipment and also the whole power plant. Moreover, a new exergy benchmark as exergy losses per unit of output power is defined. In general, exergy destruction rate of each equipment in the plant under steady-state thermodynamic conditions over a specified control volume can be calculated from the following equation[22,61]:

$$Ex_D = \sum (Ex)_{in} - \sum (Ex)_{out} + \sum \left(Q\left(1-\frac{T_0}{T}\right)\right)_{in} - \sum \left(Q\left(1-\frac{T_0}{T}\right)\right)_{out} \pm \dot{W} \quad (8)$$

$(Ex)_{in}$ and $(Ex)_{out}$ in the right side of the above equation are the exergy flow which is entered and leaved the specified control volume respectively. Heat exergy related terms are shown in the third and fourth of above formulation. The selected reference temperature is indicated by and Q is defined as the steady temperature heat transfer (at temperature of T) rate across the system boundaries. The last term represents the done or given work transfer rate amount to or from the control volume. Here, only physical exergy corresponding to the crossing mass flows across the control volume is regarded and calculated as[22,61]:

$$Ex = \dot{m}\left((h-h_0) + T_0(s-s_0)\right) \quad (9)$$

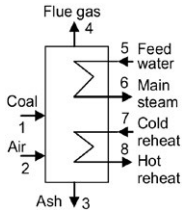In above physical exergy defining equation h and s indicate the specific enthalpy and entropy respectively.
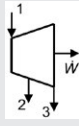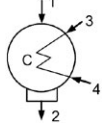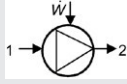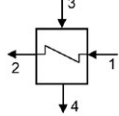
Exergy analysis is performed to find exergy efficiency to obtain an indicator which expresses the whole system or an individual equipment performance. Exergy efficiency is calculated on the basis of published approaches which define the product and fuel exergy amounts. The total consumed exergy resource is presented by fuel exergy, whereas the favorable commodity of the plant and its corresponding exergy is indicated by product exergy.[61] Similarly, the calculation procedure to obtain the exergy destruction and exergy efficiency of major devices in a coal-fired power plant is presented in Table 1.

Summing the exergy destruction occurred in each equipment resulted in the total exergy destruction rate of the power plant:

$$Ex_{D,total} = \sum Ex_{D,i} = Ex_{D,B} + Ex_{D,T} + Ex_{D,C} + Ex_{D,P} + Ex_{D,H}. \quad (10)$$

In general, any thermal power plant's exergy efficiency which is coal-fired can be calculated through following formulation:

TABLE 1 Exergy analysis equations for major devices of a thermal power plant[6]

Component name	Component figure	Exergy destruction rate	Exergy efficiency
Boiler	Flue gas 4; 5 Feed water; 6 Main steam; Coal 1; 7 Cold reheat; Air 2; 8 Hot reheat; Ash 3	$\dot{Ex}_{D,B} = \dot{Ex}_1 + \dot{Ex}_2 + \dot{Ex}_5 + \dot{Ex}_7 - \dot{Ex}_3 - \dot{Ex}_4 - \dot{Ex}_6 - \dot{Ex}_8$	$\eta_{Ex,B} = (\dot{Ex}_6 - \dot{Ex}_5) + (\dot{Ex}_8 - \dot{Ex}_7) / (\dot{Ex}_1 + \dot{Ex}2) - (\dot{Ex}_3 + \dot{Ex}_4)$
Turbine	1; W; 2 3	$\dot{Ex}_{D,T} = \dot{Ex}_1 - \dot{Ex}_2 - \dot{Ex}_3 - \dot{W}$	$\eta_{Ex,T} = \dot{W}/\dot{Ex}_1 - \dot{Ex}_2 - \dot{Ex}_3$
Condenser	1; 3; C; 4; 2	$\dot{Ex}_{D,C} = \dot{Ex}_1 + \dot{Ex}_3 - \dot{Ex}_2 - \dot{Ex}_4$	$\eta_{Ex,C} = (\dot{Ex}_4 - \dot{Ex}_3)/(\dot{Ex}_1 - \dot{Ex}_2)$
Pump	$\dot{W}$; 1 2	$\dot{Ex}_{D,P} = \dot{Ex}_1 + \dot{W} - \dot{Ex}_2$	$\eta_{Ex,P} = (\dot{Ex}_1 - \dot{Ex}_2)/\dot{W}$
Feed water heater	3; 2 1; 4	$\dot{Ex}_{D,H} = \dot{Ex}_1 + \dot{Ex}_3 - \dot{Ex}_2 - \dot{Ex}_4$	$\eta_{Ex,H} = (\dot{Ex}_2 - \dot{Ex}_1)/(\dot{Ex}_3 - \dot{Ex}_4)$

$$\eta_{ex} = \frac{\dot{W}_{Net}}{\dot{m}_{coal} ex_{coal}}, \tag{11}$$

where ex_{coal} represents the chemical exergy of coal burned in the power plant. This value is not fixed since the coal chemical composition exploited from each mine is different. Here, the typical reported value for coal chemical exergy is applied to the calculation.[62] In this study in addition to exergy efficiency, another benchmark is developed which is the exergy loss rate per output unit power and is formulated as follows:

$$\xi = \frac{Ex_{D,total}}{\dot{W}_{Net}}. \tag{12}$$

Performing energy and exergy analysis gives this opportunity to evaluate the power plant performance through thermodynamic modeling and also demonstrate the possible feasible steps toward improving the power plant total performance.

2.1.3 | Literature

In this study, a cumulative coal-fired thermal power plant is considered to be analyzed by applying various approaches leading to improve inefficiencies. These approaches consist of different techniques such as reduction in the condenser pressure, steam superheating, surging in the amount of boiler pressure, regenerative and reheat Rankine cycle as presented in Figure 2.

Thermal power plants consuming coal as fuel generally operate based on Rankine cycle. Ideal vapor power cycle is not practical due to some considerations like moisture content at turbine blades or pumping a two-phase fluid in pumping mechanism. One of the beneficial methods to overcome these defects is steam superheating in the boiler and its complete condensation in the condenser.[64]

Coal is the most common fuel utilized in India. Therefore, most of the power plants use coal as fuel for electricity generation. Generally, coal-fired power plants in this country work on subcritical steam; however, there are few plants utilizing supercritical steam parameters. The vast majority of plants have efficiency lower than 35% working with indigenous high ash coal. In recent years, considerable attempts are made to promote thermal power plants using supercritical technologies with high efficiency.

Mathematical models for economic and exergoeconomic analyses of coal-fired power plant can be used.[65,66] In the literature, there are several studies related to energetic and exergetic performance of thermal power plants consuming coal as fuel. For example, it is possible to analyze power plants based on metallurgical and chemical aspects using exergy analysis.[64,67] Exergy facilitates performance evaluation of thermal power plant since it enables us to easily understand type, magnitude, locations of losses, and wastes.[67] As it was mentioned, exergy analysis is a powerful method

for evaluating both energy quantity and quality in coal-fired plants by utilizing given data for various conditions.[34,68-74] Based on results, exergy loss in the boiler can be decreased by appropriate preheating of air at the entrance of the boiler and decreasing fuel to air ratio.[33,75] Wang et al[76] proposed the relationship between power plant's efficiency and irreversibilities in the rotating preheater (used for air) using exergy analysis.[77] Proposed operation and maintenance decisions are carried out by applying exergy analysis for a 500 MW steam turbine power plant.[78]

Exergy analysis is conducted in a large-scale ultra-supercritical coal-fired power plant. In a study, Rankine cycle working with ammonia-water was compared to regenerative Rankine power generation cycle by applying second law of thermodynamics and exergy analysis.[79] Exergy topological approach was applied in an organic Rankine cycle and in micro-organic Rankine heat engines in order to represent an approximation of the exergy destruction by utilizing various working fluid.[11,80-86] They carried out their research on the simulation and exergy analysis of a 600 MWe and 800 MWe Oxy combustion pulverized coal-fired power plant. Blanco-Marigorta et al[87] identified the location, magnitude and the thermodynamic reasons for inefficiencies in a solar thermal power plant using exergy analysis.

Pressures of the first and second reheat were optimized by utilizing energy efficiency and exergy balance.[88] A set of optimization cycle was performed based on energy evaluation modeling and irreversibilities evaluation modeling for components such as a turbine, condenser, boiler and the combustion chamber to obtain the optimum possible pressures value correspondence to the highest amount of energy and exergy efficiencies for a double-reheat steam power plant.[88] In supercritical coal-fired power plants, multiobjective optimization can be applied for searching the decision space frontier in a single run.[89] A system simulation calculation model has been carried out to explore the exergy destruction along with pollutant emission characteristics of the plant.[89] In a pulverized coal-fired power plant, the influences of various operating conditions and parameters on the performance of each part of the plant using second law analysis have been observed. Additionally, a study based on thermo-economic has been proposed for the cost formation of the plant.[90,91] Exergy and techno-economic analyses have been employed for optimizing of a double reheat system applied in an ultra-supercritical power plant. A correlation was derived for both exergy loss and capital cost. In addition, it is suggested that devices in plant approximately conform to a specific ratio value which shows the good trade-off between exergy losses and capital costs.[92] Therefore, thermo-economic is a promising tool for diagnosing of complex energy systems.[93] Exergy efficiency analysis through irreversibility helped out to reduce thermal irreversibility of the Kalina cycle using ammonia-water mixture as the working substance.[94] Moreover, the performance of the cycle can be assessed using the exergy
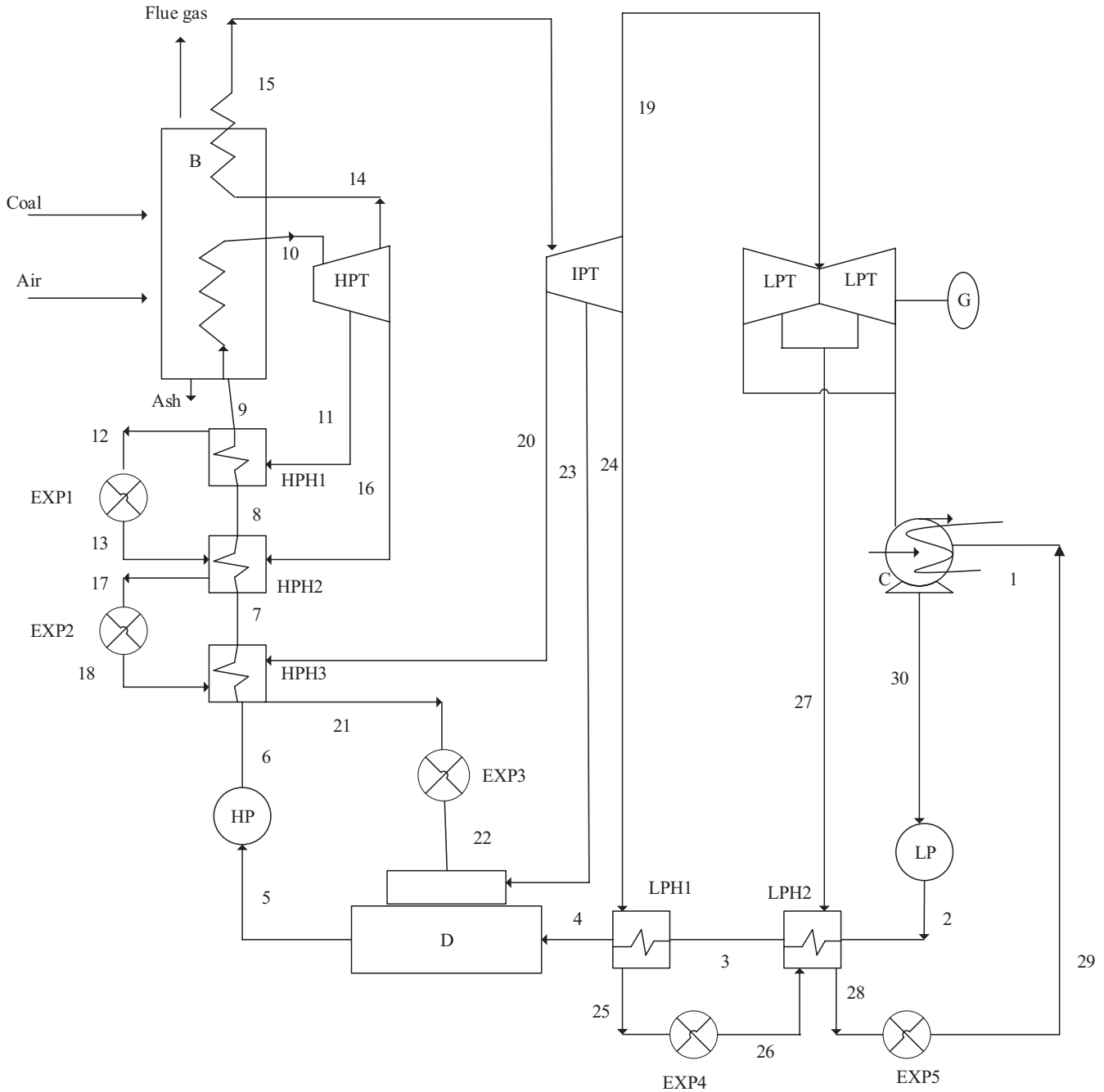
FIGURE 2 Schematic of coal-fired thermal power plant[63]

efficiency in a high temperature Kalina cycle system.[95] Modi and Haglind [96] investigated the advantage of utilizing Kalina cycle for a direct steam generation, central receiver solar thermal power plant with high temperature and pressure steam. Besides, the thermodynamic performance of Kalina cycle was compared with a simple Rankine cycle using exergy efficiency of the plant. Singh et al[97] optimized Kalina cycle which was coupled with a coal-fired power plant by applying energy and exergy analysis.

As it was mentioned, several studies have been conducted on both energy and exergy analyses of power plants with

different capacities working based on coal firing.[14,98-100] In a steam power plant, both exergy and energy were analyzed.[101,102] Vandani, Bidi, and Ahmadi.[103] Gonca investigated irreversible single reheat Rankine cycle and the double reheat Rankine cycle and analyzed cycles based on thermal and exergy efficiencies, exergetic performance criterion, net specific work and exergy destruction.[104] In another research, the performance of several coal-fired power plants were analyzed and compared by applying energy and exergy approaches, which facilitate designing process and assessment of inefficiencies.[6] Nasruddin et al[105] conducted a study on
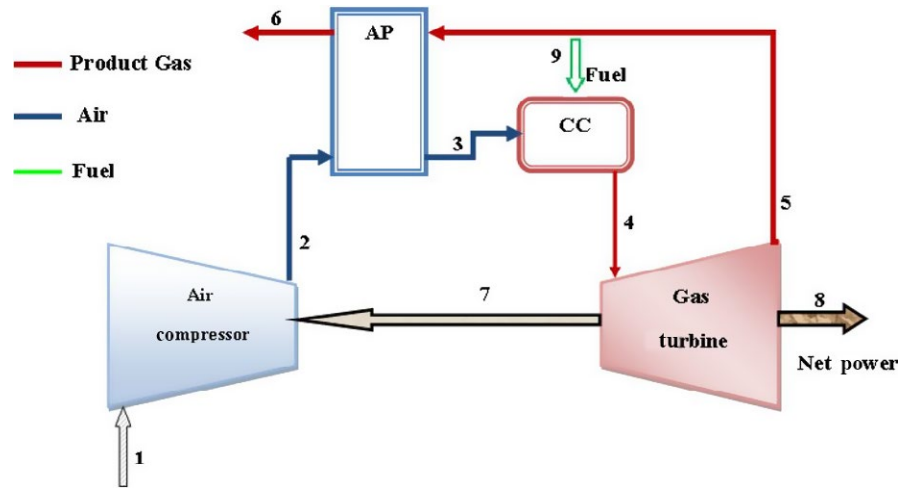
FIGURE 3 The schematic design of a gas turbine power plant[106]

Kalina cycle system, utilizing the mixture of water and ammonia, and analyzed it based on energy and exergy.

2.2 | Natural-gas-fired power plant

2.2.1 | Energy analysis

A simulation is developed in Matlab software in order to obtain the optimal conditions for physical and thermal design variables of the studied plant.

Through simulation procedure, the gas turbine's temperature profile, exergy amount, and inlet and outlet enthalpy at each line are obtained to be utilized in the multiobjective optimization procedure. Energy conservation law is considered for every part of the gas turbine power plant demonstrated in Figure 3 and the following balance equation are resulted:

Air compressor

$$T_2 = T_1 \left(1 + \frac{1}{\eta_{AC}} \left(r_{AC}^{\frac{\gamma_a - 1}{\gamma_a}} - 1 \right) \right) \tag{13}$$

$$W_{AC} = \dot{m}_a C_{pa} (T_2 - T_1) \tag{14}$$

In the performed investigation, the term C_{pa} is regarded as a function of temperature and calculated as follows[107]:

$$C_{pa}(T) = 1.048 - \left(\frac{3.83T}{10^4} \right) + \left(\frac{9.45T^2}{10^7} \right) \\ - \left(\frac{5.49T^3}{10^{10}} \right) + \left(\frac{7.29T^4}{10^{14}} \right) \tag{15}$$

Air preheater

$$\dot{m}_a (h_3 - h_2) = \dot{m}_g (h_5 - h_6) \eta_{AP} \tag{16}$$

$$\frac{P_3}{P_2} = (1 - \Delta P_{CC}). \tag{17}$$

Combustion chamber (CC)

$$\dot{m}_a h_3 + \dot{m}_f LHV = \dot{m}_g h_4 + (1 - \eta_{cc}) \dot{m}_f LHV \tag{18}$$

$$\frac{P_4}{P_3} = (1 - \Delta P_{CC}) \tag{19}$$

The combustion governing equations are:

$$\lambda C_{x1} H_{y1} + (x_{O_2} O_2 + x_{N_2} N_2 + x_{H_2O} H_2O + x_{CO_2} CO_2 + x_{Ar} Ar) \rightarrow \\ y_{CO_2} CO_2 + y_{O_2} O_2 + y_{N_2} N_2 + y_{H_2O} H_2O + y_{NO} NO + y_{CO} CO + y_{Ar} Ar) \\ y_{CO_2} = (\lambda x_1 + x_{CO_2} - y_{CO_2}) \\ y_{N_2} = (x_{N_2} - y_{NO}) \\ y_{H_2O} = \left(x_{H_2O} + \frac{\lambda y_1}{2} \right) \\ y_{O_2} = \left(x_{O_2} - \lambda x_1 - \frac{\lambda y_1}{4} - \frac{y_{CO}}{2} - \frac{y_{NO}}{2} \right) \\ y_{Ar} = x_{Ar} \\ \lambda = \frac{n_f}{n_{air}} \tag{20}$$

Gas turbine

$$T_5 = T_4 \left(1 - \eta_{GT} \left(1 - \left(\frac{P_4}{P_5} \right)^{\frac{1 - \gamma_g}{\gamma_g}} \right) \right) \tag{21}$$

$$W_{GT} = \dot{m}_g C_{pg} (T_5 - T_6) \tag{22}$$

$$\dot{W}_{Net} = \dot{W}_{GT} - \dot{W}_{AC} \tag{23}$$

$$\dot{m}_g = \dot{m}_f + \dot{m}_a \tag{24}$$

Here, as mentioned earlier, the specific heat, C_{pg}, is defined as a temperature dependent function[107]:

$$C_{pg}(T) = 0.991 - \left(\frac{6.997T}{10^5}\right) + \left(\frac{2.712T^2}{10^7}\right) - \left(\frac{1.2244T^3}{10^{10}}\right).$$

(25)

In the above equation, T denotes temperature of the gas and C_{pg} is the specific heat of the gas at temperature equal to T.

The governing mass and energy conservation equations are solved by a numerical method and temperature and enthalpy are determined for all sections in the power plant.

It must be highlighted that following fundamental assumptions are made in the thermodynamic modeling procedure[14,50,51,107]:

- Steady-state condition is regarded for all of the processes in the power plant.
- Air and also the combustion products are considered to follow the ideal-gas mixture law.
- Natural gas is regarded as a feeding fuel to the burner of the combustion chamber (CC).
- All equipment employed in the plant are considered to work under adiabatic condition.
- A specific amount is defined for the associated heat loss from the combustion chamber (CC), 3% of the lower heating value (LHV) for the used fuel in the CC.
- Reference thermodynamic condition is considered as $P_0 = 1.01$ bar and $T_0 = 293.15$ K.
- 3% pressure drop is assumed to take place in the preheater and also in the combustion chamber (CC).

2.2.2 | Exergy analysis

Four types of Exergy are defined. Among these four types, physical and chemical exergy are the major type which considered in almost every case of exergy analysis. Similar to other thermodynamic investigation in power plants, since there is no significant changes in velocity and height, the terms for kinetic exergy and potential exergy are neglected.[21,22,49,57,61,108,109] The physical exergy is the highest achievable theoretical work from the interaction of the system from an operational condition to a defined dead state condition.[21] On the other hand, the chemical exergy is defined for a material as the exergy correspondence to switch between its chemical compositions in the system to its chemical equilibrium state. Chemical exergy plays a significant role in processes that are associated with combustion. The following exergy balance, as it is shown in Equation (26), is resulted by applying thermodynamic laws to a determined control volume of the system (1st and 2nd):

$$Ex_Q + \sum_i m_{inlet,i} ex_{inlet,i} = Ex_W + Ex_D + \sum_e m_{outlet,e} ex_{outlet,e}$$

(26)

Ex_D represents the exergy destruction amount. The other employed terms are defined as follows:

$$Ex_Q = \left(1 - \frac{T_0}{T_i}\right) Q_i \text{ and } Ex_W = \dot{W}$$

(27)

$$ex = ex_{ph} + ex_{ch}.$$

(28)

Ex_Q represents the exergy associated to the transferred heat to or from the system and transfer and Ex_W, is defined as the crossed work from the control volume boundaries. T is regarded as the absolute temperature (K) and (0) refers to the surroundings thermodynamic conditions. In overall, the total exergy is obtained by summing the physical and chemical exergy:

$$Ex = Ex_{ph} + Ex_{ch}$$

(29)

$$Ex = \dot{m}.ex$$

The chemical exergy of a specific mixture is simply obtained by applying following equation[21,22,109]:

$$ex_{mix}^{ch} = \sum_{i=1}^{n} x_i ex_i^{ch} + RT_0 \sum_{i=1}^{n} x_i \ln x_i$$

(30)

ξ ratio is used to evaluate the exergy of the fuel:

$$\xi = \frac{ex_f}{LHV_f}$$

(31)

ξ is assume to be close to unity for almost every conventional used gaseous fuels. It is assumed that methane is the main used fuel in the power plant and it can be presented in various forms such as $\xi_{CH_4} = 1.06$ [21,22] to perform exergy analysis in this investigation, first the amount of exergy at each state is determined and then by drawing a control volume over each component, exergy variation and the resulted exergy destruction are determined. It is found that combustion chamber (CC) is the major Irreversibility source among the components since the combustion process and the corresponded chemical reactions are

TABLE 2 The exergy destruction rate and exergy efficiency equations for each employed equipment of the power plant[106]

Components	Exergy destruction rate	Exergy efficiency
Compressor	$\dot{E}_{D,AC} = \dot{E}_1 - \dot{E}_2 - \dot{E}_{W,AC}$	$\eta_{ex,AC} = \frac{\dot{E}_2 - \dot{E}_1}{\dot{W}_{AC}}$
Combustion chamber (CC)	$\dot{E}_{D,CC} = \dot{E}_3 + \dot{E}_9 - \dot{E}_4$	$\eta_{ex,CC} = \frac{\dot{E}_4}{\dot{E}_3 + \dot{E}_9}$
Gas turbine (GT)	$\dot{E}_{D,GT} = \dot{E}_C - \dot{E}_D - \dot{W}_{GT}$	$\eta_{ex,GT} = \frac{\dot{W}_{GT}}{\dot{E}_C - \dot{E}_D}$
Air preheater (AP)	$\dot{E}_{D,AP} = \sum_{i,AP} \dot{E} - \sum_{e,AP} \dot{E}$	$\eta_{ex,AP} = 1 - \frac{\dot{E}_{D,AP}}{\sum_{i,AP} \dot{E}}$

intrinsically irreversible.[21,109] It is monitored that high amount of exergy destruction is resulted in the air pre-heater heat exchanger. This is resulted because of the presence of large temperature gradient between the hot and cold flowing fluid in the preheater. Table 2 illustrates the calculated exergy destruction rate and exergy efficiency

TABLE 3 Operating conditions of the studied gas turbine, Shahid Salimi Gas Turbine Power Plant[106]

Name	Unit	Value
Natural gas mass flow rate to CC	kg/s	8.44
Air mass flow rate	kg/s	491.55
Lower heating value of natural gas	kJ/kg	50 916.96
Compressor isentropic efficiency	%	0.82
Gas turbine isentropic efficiency	%	0.86
Air preheater effectiveness	%	0.82
Compressor pressure ratio	—	10.1
Gas turbine pressure ratio	—	9.49
Output power	MW	132

for all equipment employed in the power plant (Figure 3). The operating conditions of the studied gas turbine including feeding fuel mass flow rate and its calorific value, net output electrical work and compressor's efficiencies are reported in Table 3.

2.2.3 | Literature

In addition to coal-fired power plants, several studies have focused on power plants working with gas turbines. Exergy analysis can be used to evaluate performance of heavy gas turbines.[110] The highest level of exergy destruction occurs in combustion chamber and it can be reduced by increasing pressure ratio in the cycle depending on compressor.[34,75,111] Therefore, plant efficiency is higher in full load working compared with part-load operation. Moreover, surging in pinch points reduces the efficiency of the plant. Khaldi et al[112] analyzed a power plant working with twin gas turbine in Algeria based on exergy analysis. Abdul Khaliq[113] investigated the influence of several parameters on exergy destruction of each part using second law of thermodynamics in trigeneration system working by gas turbine. The

FIGURE 4 Schematic of gas turbine trigeneration system[113]
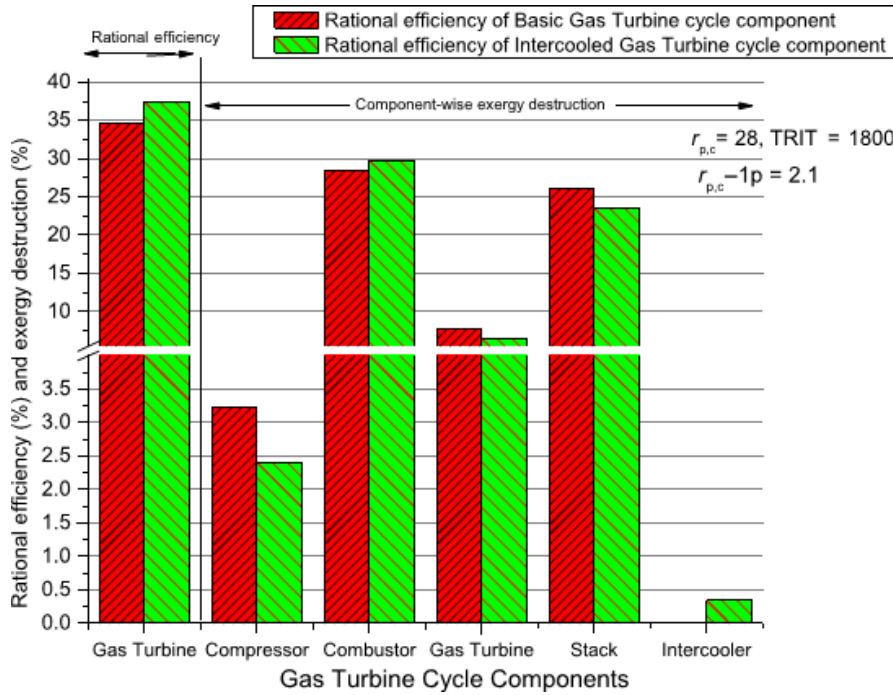
FIGURE 5 Rational efficiency and component-wise destruction of exergy[115]

schematic of the system is shown in Figure 4. Based on exergy analysis, it was observed that the highest share of exergy destruction occurred in combustion process which was more than 80% of total exergy destruction.

Amrollahi et al[114] investigated a combined-cycle power plant which had a unit to capture CO_2. The fuel of this plant was natural gas, Suggestions for integrated chemical absorption process were represented by applying exergy analysis in order to work more efficiently. Kumari[115] perform

a research on the basic-gas-turbine and intercooled-gas-turbine cycles and analyzed the influence of several cycle working factors on the performance of the mentioned cycles. The obtained results for rational efficiency and component-wise destruction of exergy for the investigated cycles are shown in Figure 5.

Researchers have conducted several studies on gas turbine power plants using exergy and exergoeconomic analyses. As an illustration, optimization based on exergy

FIGURE 6 Schematic of proposed combined cycle[125]

FIGURE 7 Exergy flow in the power plant[125]

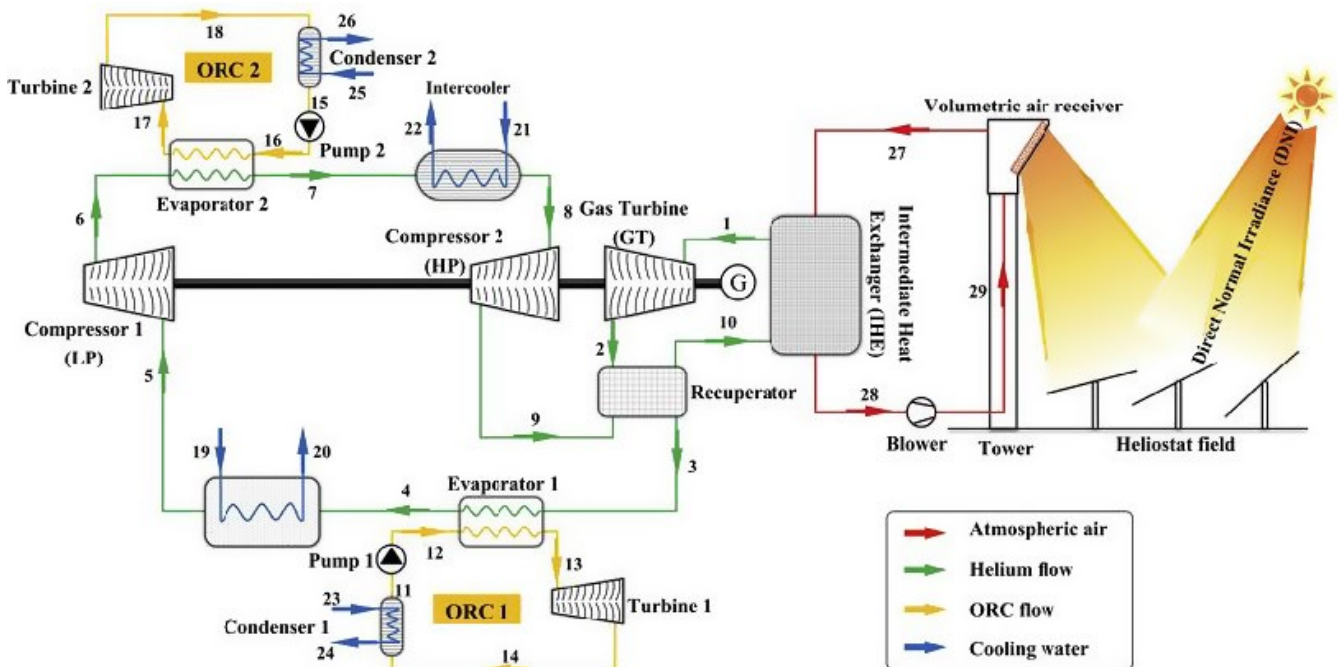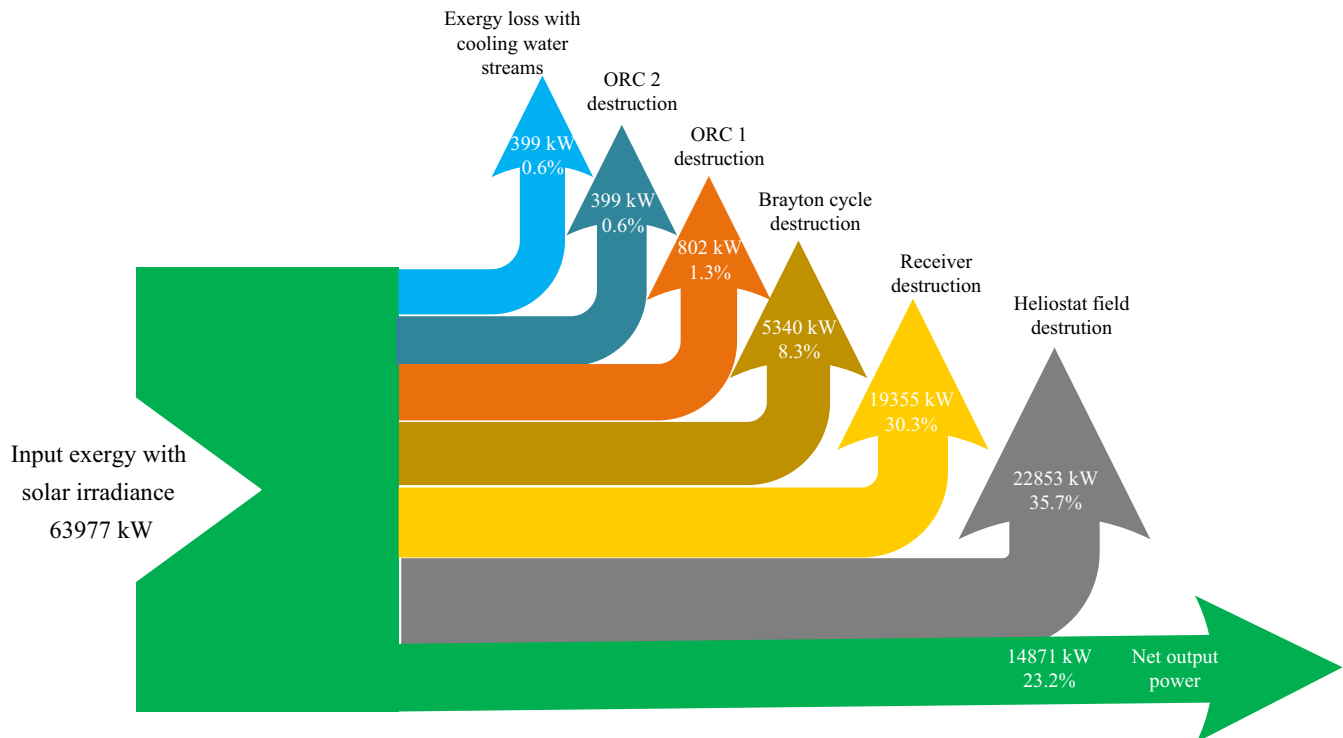and exergoeconomic analyses was done by applying genetic algorithm optimization technique.[116] Moreover, Kaviri et al[117] performed exergy optimization on a power plant working with gas turbine. Chen et al[118] analyzed and optimized the performance of an open-cycle regenerator gas-turbine power plant. Ahmadi et al[106] studied power plant performance with gas turbine and presented a modeling for both exergoeconomic and thermodynamic aspects.[119] Having investigated the influence of reference temperature on exergy and exergoeconomic parameters of a natural-gas-fired thermal plant, Ehyaei et al[120] analyzed a power plant working with conventional gas turbine and performed exergy, economic, and environmental analysis in order to evaluate the influence of inlet fogging on the efficiencies defined based on first and second laws of thermodynamics. Lebele-Alawa et al[121] analyzed a 20MW gas turbine power plant based on energy and exergy concepts. In a study, sizing and performance of a decentralized power generation plant working with biomass as fuel were analyzed under various working conditions such as different TIT, pressure ratio of the cycle and temperature differences of cold end of heat exchanger.[44] Fagbenle et al[122] conducted a study on integrated gasification steams injected gas turbine plant consuming biogas as fuel and performed exergy and energy analyses. Reheat combined Brayton/Rankine power cycle can be analyzed thermodynamically by applying second law method.[47,123] Irreversible regenerative Brayton heat engine with

external as well as internal irreversibility has been parametrically investigated.[124]

Zare et al[125] investigated a Brayton cycle operating with Helium as working fluid and two organic Rankine cycle as illustrated in Figure 6. The exergy efficiency of the power plant is obtained and is approximately equal to 30%. The values of calculated exergy destruction for various components are presented in Figure 7.

2.3 | Combined-cycle power plant

2.3.1 | Energy analysis

A simulation was performed with Matlab software to calculate the optimal operational status of the system's design variables. Multi-objective optimization was carried out to find temperature profiles of gas and steam in the CCPP, and also to specify the enthalpy and exergy of each plant line at the input and output of each equipment. The schematic design of the CCPP system is shown in the Figure 8 and the Energy balances and governing equation for each employed equipment are explained in the following.

Air compressor
Air is delivered to the compressor at ambient pressure (1 bar) and temperature T_1. The outlet compressor temperature is affected by the compressor isentropic efficiency (η_{AC}), the compressor pressure ratio (r_{AC}), and also the specific

FIGURE 8 Schematic of a combined cycle power plant with an auxiliary fired heater[126]
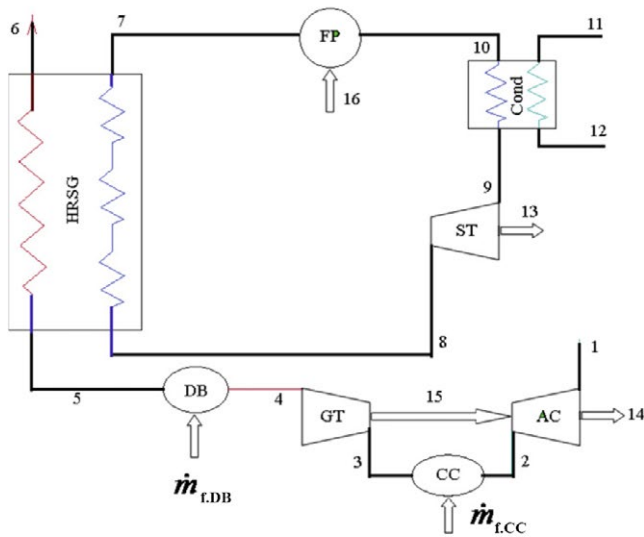
Point number	Specification
1	Inlet air entering compressor
2	Outlet air from compressor
3	Combustion gases exiting combustion chamber
4	Outlet hot gases exiting gas turbine
5	Combustion outlet gases exiting duct burner
6	Outlet gases exiting HRSG
7	Supplied water entering HRSG
8	Superheated steam entering steam turbine
9	Outlet steam from steam turbine
10	Saturated liquid entering feed water pump
11	Inlet cooling water
12	Outlet water exiting condenser
13	Steam turbine net output power
14	Gas turbine net output power
15	Compressor work
16	Pump work

heat. The compressor outlet temperature is calculated as follows:

$$T_2 = T_1 \left(1 + \frac{1}{\eta_{AC}} \left(r_{AC}^{\frac{\gamma_a - 1}{\gamma_a}} - 1 \right) \right). \tag{32}$$

To calculate the compressor work rate, parameters including mass flow rate of the input air ($\dot{m}_a$), air specific heat and the temperature difference between input and output of the compressor are needed to be specified. The compressor work system can be calculated by following expression:

$$W_{AC} = \dot{m}_a C_{pa} \left(T_2 - T_1 \right). \tag{33}$$

In the employed equations, γ_a indicates the air specific heat ratio, and C_{pa} (the air specific heat) is temperature function and obtained by Equation (34)[127]:

$$C_{pa}(T) = 1.048 - \left(\frac{3.83T}{10^4} \right) + \left(\frac{9.45T^2}{10^7} \right) - \left(\frac{5.49T^3}{10^{10}} \right) + \left(\frac{7.29T^4}{10^{14}} \right). \tag{34}$$

Combustion chamber (CC)

The variation of air mass flow rate, lower heating value of the fuel (LHV), and the efficiency of the combustor should be specified to calculate the combustion chamber's outlet properties:

$$\dot{m}_a h_2 + \dot{m}_f LHV = \dot{m}_g h_3 + \left(1 - \eta_{cc} \right) \dot{m}_f LHV \tag{35}$$

The pressure drop across the chamber is regarded to calculate the outlet pressure of the combustion chamber, and calculated by Equation (36):

$$\frac{P_3}{P_2} = \left(1 - \Delta P_{CC} \right) \tag{36}$$

Here, ΔP_{CC} denotes the pressure loss across the combustion chamber and η_{cc} is the efficiency of the combustor. The combustion reaction specifications and its related-species coefficients can be stated through following equations, Equation (37):

$$\begin{aligned}
&\lambda C_{x1} H_{y1} + \left(x_{O_2} O_2 + x_{N_2} N_2 + x_{H_2O} H_2O + x_{CO_2} CO_2 + x_{Ar} Ar \right) \rightarrow \\
&y_{CO_2} CO_2 + y_{O_2} O_2 + y_{N_2} N_2 + y_{H_2O} H_2O + y_{NO} NO + y_{CO} CO + y_{Ar} Ar) \\
&y_{CO_2} = \left(\lambda x_1 + x_{CO_2} - y_{CO_2} \right) \\
&y_{N_2} = \left(x_{N_2} - y_{NO} \right) \\
&y_{H_2O} = \left(x_{H_2O} + \frac{\lambda y_1}{2} \right) \\
&y_{O_2} = \left(x_{O_2} - \lambda x_1 - \frac{\lambda y_1}{4} - \frac{y_{CO}}{2} - \frac{y_{NO}}{2} \right) \\
&y_{Ar} = x_{Ar} \\
&\lambda = \frac{n_f}{n_{air}}
\end{aligned} \tag{37}$$

Gas turbine

The temperature in the outlet of the gas turbine can be calculated by regarding the gas turbine isentropic efficiency (η_{GT}), the inlet temperature of the gas turbine (T_3) and also the pressure ratio between outlet and inlet of the gas turbine $\left(\frac{P_3}{P_4} \right)$ as follows:

$$T_4 = T_3 \left(1 - \eta_{GT} \left(1 - \left(\frac{P_3}{P_4} \right)^{\frac{1 - \gamma_g}{\gamma_g}} \right) \right). \tag{38}$$

The output work of the gas turbine is calculated as follows:

$$W_{GT} = \dot{m}_g C_{pg} \left(T_3 - T_4 \right), \tag{39}$$

where $\dot{m}_g$ indicates the gas turbine mass flow rate and obtained as follows:

$$\dot{m}_g = \dot{m}_f + \dot{m}_a. \tag{40}$$

The total useful output power of the CCPP system, indicated as $\dot{W}_{Net}$ can be stated as:

$$\dot{W}_{Net} = \dot{W}_{GT} - \dot{W}_{AC} \tag{41}$$

In which C_{pg} is taken as a temperature function and calculated as follows[2]:

$$C_{pg}(T) = 0.991 - \left(\frac{6.997T}{10^5}\right) + \left(\frac{2.712T^2}{10^7}\right) - \left(\frac{1.2244T^3}{10^{10}}\right).$$

(42)

Duct burner

The auxiliary burner system is provided to burn the remained fuel in order to raise up the exhaust gas temperature that is transmitted through the HRSG. The following equation balance is written for the duct burner:

$$\dot{m}_g h_4 + \dot{m}_{f,DB} LHV_f = \dot{m}_5 h_4 + (1 - \eta_{DB})\,\dot{m}_{f,DB} LHV.$$

(43)

In above equation, Equation 12, LHV is the natural gas lower heating value and η_{DB} indicates the duct burner combustion efficiency, which is considered to be 94%, based on reported values in well-known references.[128]

Heat recovery steam generator (HRSG)

The energy balance should be written for gas and water in all part of the HRSG system, Equations (44), (45), and (46), and solve simultaneously to obtain gas temperature and water properties.

$$\dot{m}_w (h_a - h_7) = \dot{m}_g C_{pg} (T_c - T_6)$$

(44)

$$\dot{m}_w (h_b - h_a) = \dot{m}_g C_{pg} (T_d - T_c)$$

(45)

$$\dot{m}_w (h_8 - h_b) = \dot{m}_g C_{pg} (T_5 - T_c).$$

(46)

In above equations, the used C_{pg} is obtained by Equation (42).

Steam turbine (ST)

The output work of the steam turbine which is demonstrated in Figure 8 is calculated as follows:
The isentropic efficiency of the steam turbine is stated as

$$\dot{m}_w (h_8 - h_9) = W_{ST}$$

(47)

follows:

$$\eta_{ST} = \frac{W_{ST,act}}{W_{ST,is}}.$$

(48)

The whole CCPP system performance is assessed by calculating the above cycle energy efficiency (Gas turbine power cycle), bottom cycle energy efficiency (steam turbine unit), and also the total CCPP energy efficiency through following equations:

$$\eta_{GT} = \frac{W_{GT} - W_{AC}}{Q_{in,CCPP}}$$

(49)

$$\eta_{ST} = \frac{W_{ST} - W_{FP}}{Q_{in,CCPP}}$$

(50)

$$\eta_{CCPP} = \frac{W_{GT} - W_{AC} + W_{ST} - W_{FP}}{Q_{in,CCPP}}.$$

(51)

Numerical solving procedure is performed on the above equations to calculate the temperature and enthalpy for all the plant's flow. Following facilitating assumptions similar to other investigations are regarded[21,128,129]:

- Steady- state and steady-flow conditions are taken for all processes.
- Ideal-gas mixtures governing states are considered for the products of the combustion unit and also the input air.
- Natural gas is injected to the combustion chamber as the feeding fuel.
- 3% of the entering fuel LHV is considered as the heat loss wasted in the combustion chamber. In addition, the other employed equipment were regarded adiabatic.[128]
- The reference thermodynamic statuses are defined as $P_0 = 1.01$ bar and $T_0 = 293.15$ K.

2.3.2 | Exergy analysis

Exergy can be stated into four terms including physical, chemical, kinetic, and potential. Kinetic and potential exergy terms are neglected in this investigation since there is no significant changes in both elevation and speed.[25,57,61,130] The highest achievable theoretical work is considered as physical exergy and stated as a result of the interaction between the studied system and the determined reference environment till it reaches to its equilibrium state.[25] The transformation of the system's chemical composition condition from the present status to the chemical composition at the reference environment is called Chemical exergy. The mostly considered Chemical exergy is for fuels. By regarding 1st and 2nd laws of thermodynamics, the following exergy balance can be written:

$$Ex_Q + \sum_i m_{inlet,i} ex_{inlet,i} = Ex_W + Ex_D + \sum_e m_{outlet,e} ex_{outlet,e}.$$

(52)

In above balance equation, Ex_D, the exergy destruction and other employed terms are defined as follows[6,11]:

$$Ex_Q = \left(1 - \frac{T_0}{T_i}\right) Q_i$$

(53)

$$Ex_W = W$$

(54)

$$ex = ex_{\mathrm{ph}} + ex_{\mathrm{ch}} \tag{55}$$

$$ex_{\mathrm{ph}} = (h - h_0) + T_0 (s - s_0), \tag{56}$$

where Ex_Q and Ex_W are the exergy rates as a result of the occurrence of heat transfer and work across the control volume boundaries, T is considered as absolute temperature and the subscript o denotes the reference environment conditions. Here in this study, the reference environment is selected as $T_0 = 20°C$ and $P_0 = 1$ bar.

The gas mixtures chemical exergy is calculated as follows[19,25,33,131]:

$$ex_{\mathrm{mix}}^{\mathrm{ch}} = \sum_{i=1}^{n} x_i ex_i^{\mathrm{ch}} + RT_0 \sum_{i=1}^{n} x_i \ln x_i. \tag{57}$$

However, the above equation is not usable in fuel exergy calculation. Therefore, the following simplified equation is used to calculate the fuel exergy[25,34,132]:

$$\xi = \frac{ex_{\mathrm{f}}}{LHV_{\mathrm{f}}}. \tag{58}$$

The defined ratio in above equation is normally considered close to unity (it can be roughly considered as unit) for conventional gaseous fuels,[25,132] eg, $\xi_{\mathrm{CH_4}} = 1.06, \xi_{\mathrm{H_2}} = 0.985$:

In case of having general gaseous fuel composition, C_xH_y, the experimental mathematical model proposed by Dincer and Rosen can be employed to calculate ζ[25]:

$$\xi = 1.033 + 0.0169\frac{y}{x} - \frac{0.0698}{x}. \tag{59}$$

In this investigation, exergy analysis is performed on all of the involved flow and specifically for each equipment and the exergy variation is obtained. The exergy destruction amount and exergy efficiency of each individual equipment and the total power plant (CCPP) is stated through Table 4. As it is obviously clear through Table 4, the combustion chamber is the major exergy destruction (or irreversibility) source since combustion and chemical reactions cause significant heat transfer rate, considerable temperature gradient and thermal losses in the flow direction.[130,133] Whereas the large temperature differences between the hot and cold fluids is the reason for the primarily exergy destruction in the main heat exchanger of the system (the HRSG). In the work published by Ameri et al the results were so similar to the performed analysis.[130,133] Ameri et al,[130] carried out another investigation and found out the major irreversibility source of a steam power plant is the boiler due to the large instinctive temperature difference between the burners and the circulating water in the boiler tubes. In overall, in irreversible chemical reactions and in such case that temperature gradient is significantly considerable, the resulted exergy destruction amount will be higher.

2.3.3 | Exergo-economic analysis

Economic model

Exergo-economics investigation is an interdisciplinary engineering branch where each system equipment assessed thermodynamically through exergy analysis and simultaneous evaluation based on economic fundamentals. This special methodology is carried out to design and eventually fabricate exergy-efficient and cost-effective systems which is not available by performing individual energy, exergy, or either economic analysis.[134] It is recommended by some authors that in case when sufficient exergy cost is not provided, the general term thermo-economics is superior to other combinational methods of thermodynamics and economics.[61,92] Each equipment cost should be stated as a function of thermodynamic design variables to specify a dependent cost function for optimization aims.[61] This procedure firstly performed on CGAM problem.[133,135]

A parameter named flow cost rate C ($/h) is considered for each flow in the CCPP system and also the corresponding cost balance of each component can be written as follows:

TABLE 4 Expression for exergy destruction rate and exergy efficiency for combined cycle power plant components[126]

Plant component	Exergy destruction rate	Exergy efficiency
Air compressor	$\dot{Ex}_{\mathrm{D,AC}} = \dot{E}_1 - \dot{E}_2 + \dot{W}_{\mathrm{AC}}$	$\eta_{\mathrm{ex,AC}} = \frac{\dot{Ex}_2 - \dot{Ex}_1}{\dot{W}_{\mathrm{AC}}}$
Combustion chamber	$\dot{Ex}_{\mathrm{D,AC}} = \dot{E}_2 + \dot{Ex}_{\mathrm{f,CC}} - \dot{Ex}_3$	$\eta_{\mathrm{ex,AC}} = \frac{\dot{Ex}_3}{\dot{Ex}_2 + \dot{Ex}_{\mathrm{f,CC}}}$
Duct burner	$\dot{Ex}_{\mathrm{D,GT}} = \dot{E}_4 - \dot{E}_5 + \dot{Ex}_{\mathrm{f,DB}}$	$\eta_{\mathrm{ex,AC}} = \frac{\dot{Ex}_5}{\dot{Ex}_4 + \dot{Ex}_{\mathrm{f,DB}}}$
Condenser	$\dot{Ex}_{\mathrm{D,Cond}} = \sum_{i,\mathrm{Cond}} \dot{Ex} - \sum_{o,\mathrm{Cond}} \dot{Ex}$	$\eta_{\mathrm{ex,AC}} = 1 - \frac{\dot{Ex}_{\mathrm{D,Cond}}}{\sum_{i,\mathrm{Cond}} \dot{Ex}}$
Gas turbine	$\dot{Ex}_{\mathrm{D,GT}} = \dot{E}_3 - \dot{E}_4 - \dot{W}_{\mathrm{GT}}$	$\eta_{\mathrm{ex,GT}} = \frac{\dot{W}_{\mathrm{GT}}}{\dot{Ex}_3 - \dot{Ex}_4}$
HRSG	$\dot{Ex}_{\mathrm{D,HRSG}} = \sum_{i,\mathrm{HRSG}} \dot{Ex} - \sum_{o,\mathrm{HRSG}} \dot{Ex}$	$\eta_{\mathrm{ex,HRSG}} = \frac{\dot{Ex}_8 - \dot{Ex}_7}{\dot{Ex}_5 - \dot{Ex}_6}$
Steam turbine	$\dot{Ex}_{\mathrm{D,ST}} = \sum_{i,\mathrm{ST}} \dot{Ex} - \sum_{o,\mathrm{ST}} \dot{Ex}$	$\eta_{\mathrm{ex,ST}} = \frac{\dot{W}_{\mathrm{ST}}}{\dot{Ex}_{\mathrm{i,ST}} - \dot{Ex}_{\mathrm{o,ST}}}$
Pump	$\dot{Ex}_{\mathrm{D,ST}} = \dot{Ex}_{\mathrm{i,P}} - \dot{Ex}_{\mathrm{o,P}} + \dot{W}_P$	$\eta_{\mathrm{ex,P}} = \frac{\dot{Ex}_{\mathrm{i,P}} - \dot{Ex}_{\mathrm{o,P}}}{\dot{W}_P}$

$$C_{q,k} + \sum_i C_{i,k} + Z_k. = \sum_e C_{e,k} + C_{w,k}. \tag{60}$$

In overall, all the terms in cost balance equation are considered positive. Equation (61) can be derived by replacing Equation (62) in Equation (60)[92,136]:

$$c_{q,k} Ex_{q,k} + \sum_i \left(c_i Ex_i\right)_k + Z_k. = \sum_e \left(c_e Ex_e\right)_k + c_{w,k} W_k \tag{61}$$

$$C_j = c_j Ex_j. \tag{62}$$

Before applying exergo-economic analysis, it is required to determine the exergy of the fuel and the resulted product. The fuel exergy indicated the exergy source which is going to be used in order to generate product, while the exergy of the product is calculated under the considered conditions. All the resulted product and fuel expressions are stated exergetically. The fuel (C_F) and product (C_P) cost rates related to each equipment are calculated by substituting the exergy rates (Ex). There is not any cost term in cost balance model (Equation (62) which considered exergy destruction directly of each equipment. Therefore, the bearing cost for the exergy destruction of each equipment or process is not clearly stated. Through the combination exergy and exergoeconomic balances:

$$Ex_{F,k} = Ex_{P,k} + Ex_{D,k}. \tag{63}$$

The following equation can be derived to define the exergy destruction cost:

$$C_{D,k} = c_{F,k} Ex_{D,k}. \tag{64}$$

Supplementary information about the exergo-economic analysis, cost balances, and exergo-economic factors can be found in other publications.[61,134,136,137]

Moreover, various concepts have been presented so far to define the equipment's purchase cost as a function of design variables in Equation (62).[50,92,136] In this study, the cost function model recommended by Ahmadi et al[50,129,130] and Roosen et al[138] is utilized. The mentioned model is revised to be compatible with the Iran regional conditions and also its inflation rate. Through Equation (65) the capital investment cost is converted to cost per time as follows:

$$Z_k. = \frac{Z_k . CRF . \phi}{N \times 3600}. \tag{65}$$

Here, Z_k and CRF indicate the purchase cost of the kth equipment, and the capital recovery factor respectively. CRF is depended on the interest rate and equipment life time, and it is calculated as follows[61]:

$$CRF = \frac{i \times (1+i)^n}{(1+i)^n - 1}. \tag{66}$$

In above equation for calculating CRF factor, i and n indicate the interest rate and the total operating period of the system in years respectively. Also, N, in Equation (65) is the annual number of working hours for the plant, and ϕ denotes the maintenance factor, which is normally considered as 1.06.[61,75] The exergy destruction term should be first calculated from the exergy balance equation which is discussed in the previous section in order to obtain $Ex_{D,k}$, the equipment exergy destruction cost.

Cost anlaysis

In order to have an estimation on the cost of exergy destruction in each part of the investigated plant, the cost balances for each part is considered and solved in the first step. In the procedure of cost balance as represented in Equation 61, more than one inlet or outlet flows exist for some of the parts. Therefore, the number of flows for some parts which is not known is more than cost balances for the component. In order to make the problem solvable, auxiliary exergoeconomic equations are utilized.[61,126] By using Equation 61 for each part of the system with the mentioned equations, linear equation system obtained as:

$$[\dot{Ex}_k] \times [C_k] = [\dot{Z}_k]. \tag{67}$$

In the above equation, $[\dot{Ex}_k]$ is the matrix of energy rate which is obtainable by using exergy analysis. $[C_k]$ is exergetic cost vector and $[\dot{Z}_k]$ is the vector of $\dot{Z}_k$ factor which is obtainable by using economic analysis.

$$
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & \dot{Ex}_4 & -\dot{Ex}_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\dot{W}_{GT} & 0 \\
0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\dot{W}_{AC} & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{Ex}_{10} & -\dot{Ex}_g & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \dot{Ex}_g & -\dot{Ex}_g & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\dot{W}_{FP} & 0 & 0 & -\dot{W}_{ST}
\end{bmatrix}
\times
\begin{bmatrix}
\dot{C}_1 \\ \dot{C}_2 \\ \dot{C}_3 \\ \dot{C}_4 \\ \dot{C}_5 \\ \dot{C}_6 \\ \dot{C}_7 \\ \dot{C}_8 \\ \dot{C}_9 \\ \dot{C}_{10} \\ \dot{C}_{11} \\ \dot{C}_{12} \\ \dot{C}_{13} \\ \dot{C}_{14} \\ \dot{C}_{15} \\ \dot{C}_{16}
\end{bmatrix}
=
\begin{bmatrix}
0 \\ -\dot{Z}_{AC} \\ -\dot{Z}_{CC} - -\dot{C}_{f,CC} \\ -\dot{Z}_{GT} \\ 0 \\ 0 \\ -\dot{Z}_{DB} - -\dot{C}_{f,DB} \\ -\dot{Z}_{HRSG} \\ 0 \\ -\dot{Z}_{FB} \\ -\dot{Z}_{ST} \\ 0 \\ -\dot{Z}_{cond} \\ 0 \\ 0 \\ 0
\end{bmatrix}
$$

The above matrix is obtained on the basis of cost balance as:

$$\dot{C}_1 = 0$$

$$\dot{C}_1 + \dot{Z}_{AC} + \dot{C}_{15} = \dot{C}_2$$

$$\dot{C}_2 + \dot{Z}_{CC} + \dot{C}_{f,CC} = \dot{C}_3$$

$$\dot{C}_3 + \dot{Z}_{GT} = \dot{C}_{14} + \dot{C}_{15}$$

$$\dot{Ex}_4 \dot{C}_3 = \dot{Ex}_3 \dot{C}_4$$

$$\dot{W}_{AC} \dot{C}_{14} = \dot{W}_{GT} \dot{C}_{15}$$

$$\dot{C}_4 + \dot{Z}_{DB} + \dot{C}_{f,DB} = \dot{C}_5$$

$$\dot{C}_5 + \dot{Z}_{HRSG} + \dot{C}_7 = \dot{C}_6 + \dot{C}_8$$

$$\dot{Ex}_{10} \dot{C}_9 = \dot{Ex}_9 \dot{C}_{10}$$

$$\dot{C}_{10} + \dot{Z}_{FP} + \dot{C}_{16} = \dot{C}_7$$

$$\dot{C}_8 + \dot{Z}_{ST} = \dot{C}_9 + \dot{C}_{13}$$

$$\dot{Ex}_9 \dot{C}_8 = \dot{Ex}_8 \dot{C}_9$$

$$\dot{C}_9 + \dot{Z}_{Cond} + \dot{C}_{11} = \dot{C}_{12} + \dot{C}_{10}$$

$$\dot{C}_{11} = 0$$

$$\dot{Ex}_6 \dot{C}_5 = \dot{Ex}_5 \dot{C}_6$$

$$\dot{W}_{FP} \dot{C}_{13} = \dot{W}_{ST} \dot{C}_{16}.$$

In the above equations, $\dot{C}_{f,CC} = C_f \dot{m}_{f,CC}.\text{LHV}$ and $\dot{C}_{f,DB} = C_f \dot{m}_{f,DB}.\text{LHV}$ where C_f is the cost of fuel.

2.3.4 | Literature

Combine-cycle power plants (CCPPs) have been evaluated by numerous researchers based on energy and exergy concepts.[17,63,139-150] The majority of studies have focused on the effect of working parameters including TIT, compression pressure ratio, ambient temperature, and humidity on the performance of these systems and their components. Facchini et al[151] investigated a combined cycle power plant and evaluated exergy losses in different components of the system. Ibrahim et al[152] analyzed a triple pressure reheat combined cycle gas turbine plant which had a duct burner thermodynamically. Oyedepo et al[153] assessed a GT power plant and concluded that its performance would enhance by cooling the compressor intake air by applying an evaporative cooler.

In a study, conventional and advanced exergetic analyses were performed on a CCPP consuming natural gas as fuel, as shown in Figure 9.[154] In combined cycle including steam turbines, the influences of various working parameters on the performance of the cycle have been investigated by applying second law analysis.[155,156]

Boyaghchi et al[157] analyzed a real combined cycle power plant based on exergy concept. Karrabi et al[158] performed thermal and exergy analyses on the influences of supplementary firing on the heat recovery steam generator under different operating conditions such as different ambient temperatures and loads of gas turbine in a CCPP with
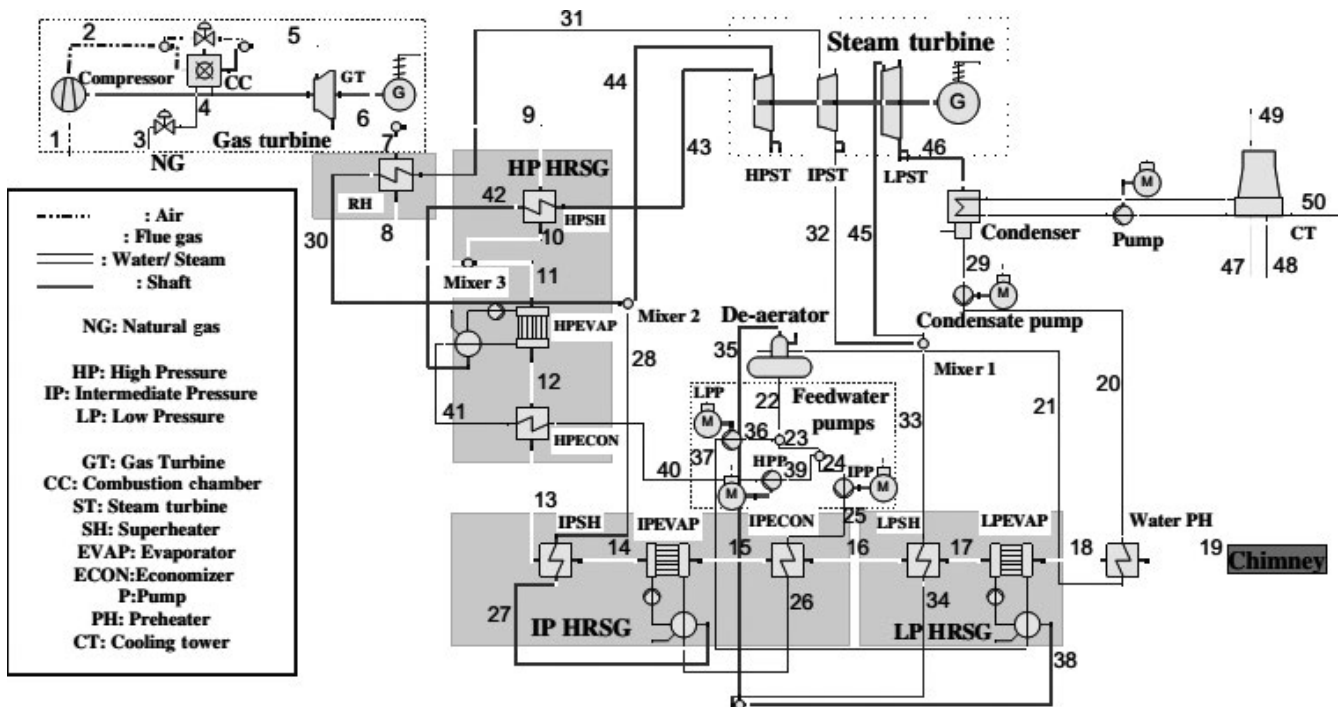

FIGURE 9 Structure of CCPP[154]

420 MW capacity. Obtained results predicted that the supplementary firing leads to achieving higher exergy loss and reduction in total exergy efficiency. Solatni et al[159] performed an advanced exergy analysis on a CCPP configuration working with an externally fired integrated combustion and biomass gasification. The result shows the potential for improvement of the overall plant systems considering interactions among the individual components. Hajabdollahi et al[108] provided a model for a heat recovery steam generator and a number of pressure levels were used in combined cycle power plants using evolutionary algorithms. Al-Sulaiman et al[160] conducted the exergy assessments of an integrated organic Rankine cycle with a biomass combustor for a trigeneration system. Haseli et al[161] presented a comparative exergy analysis of a combined fuel cell and gas turbine power plant with intercooling and reheating. They concluded that integrating a gas turbine plant with fuel cell can increase the cycle efficiency twofold. Gogoi and Talukdar[162] carried out an exergy analysis for a combined reheat regenerative steam turbine and water-LiBr vapor absorption refrigeration system. They observed the effect of temperature of vapor absorption refrigeration system component, boiler pressure, fuel flow rate, and cooling capacity on performance of equipment and total system irreversibility. Bhattacharya et al[163] investigated the influences of pressure and temperature ratios of the gas turbine system and the amount of fuel utilized in the supplementary firing chamber on both thermal and exergy efficiencies of a biomass integrated gasification combined cycle. Chen et al[164] established a combined cooling, heating and power plant model comprising of a closed Brayton cycle which was irreversible and an endoreversible four-heat-reservoir absorption refrigeration cycle. Finite time thermodynamics was employed for exergy efficiency optimization of the plant. In a natural-gas-fired combined cycle power generation unit exergy analysis was performed in the plant and the amounts of exergy destruction were presented for the components.[39]

Baghernejad and Yaghoubi[165] analyzed an integrated solar combined cycle system based on energy and exergy for both evaluating plant performance and finding locations as well as magnitude of exergy destruction. Cziesla et al[166] conducted a study on an externally fired CCPP based on exergoeconomic concept. An optimization plan was proposed for heat recovery steam generators equipment in the combined cycle power plant to increase plant efficiency and for exergoenvironmental optimization.[60,167-171] Giovanni[172] has developed a comprehensive off-design model for a 390 MWe three-pressure-level natural gas combined cycle designed in order to assess various integration schemes of solar energy with minimum equipment modifications. Their results have revealed that the highest level of incremental power output from solar at design solar irradiance reached 19 MWe

without promotion of the existing facilities. They have also observed that higher power outputs are obtainable using a steam turbine with larger size.

Binamer[173] investigated a cogeneration plant, including CCPP and METVC desalination system, by applying thermodynamic analysis. Obtained results indicated that the effects had the highest irreversibilities in the desalination system. In exergy analysis performed on desalination unit integrated with a CCPP, Elhaj et al[174] concluded that the pressure of a steam turbine, extracted steam, and the condenser, highly influence on the exergetic efficiency.

2.4 | Cogeneration and tri-generation systems

2.4.1 | Energy analysis

A tri-generation system including a biomass burner, an ORC, and a heating process is evaluated in this investigation. The schematic process of the studied system is demonstrated in Figure 10.

A heat exchanger and a single-effect absorption chiller is provided to utilize the ORC wasted heat for heating and cooling purposes respectively. It should be noted that effective waste utilization and a high efficiency ORC require a working fluid with a high critical temperature. Noctane is a conventional organic working fluid for employing in ORC plants since it provides the needed critical high temperature (569 K).[176] Therefore, this working fluid is considered as the utilized working fluid of the studied ORC. Pine sawdust is supplied to burn in the biomass burner and its specifications are stated in Table 5.

Pine sawdust is considered as the most typical waste wood product in wood industry since pine trees are a common plant species in the whole world. This availability makes it an appropriate resource in wood industry or other wood-related industries. Performing wood processing on pine wood results sawdust. Pine sawdust due to its large waste production is typically employed as a biomass. Hence, this type of biomass is considered in this investigation. Table 6 expresses the used input data in the modeling procedure of the tri-generation system.

In Table 6, the considered isentropic efficiencies for various components of the systems are represented. Moreover, inlet temperatures of pump and turbine are given. In addition, other parameters which play role in the output of modeling such as ambient conditions including temperature and pressure and heat transfer coefficients of utilized components are represented.

Several simplifying assumptions are regarded to perform energy and exergy analysis on the tri-generation system. Steady-state condition is applied on the studied system. Moreover, working under constant pressure is assumed for all equipment except pumps, valves, and ORC turbine. In

addition, complete combustion is assumed for the biomass burner. A similar model to Herlod et al[177] is used for the utilized single-effect absorption chiller. Therefore, validation of the single-effect absorption chiller is carried out by utilizing the reported data of the Herlod et al.[177]

Here, the introduced tri-generation system is modeled through energy analysis. The net electrical work of the tri-generation system is expressed as:

$$W_{net} = \eta_g W_{ot} - \frac{W_{op}}{\eta_{motor}} - \frac{W_{sp}}{\eta_{motor}}, \quad (68)$$

where W represents the work, and the amount of consumed or obtained work of generator, ORC pump, solution pump, and ORC turbine are stated by the subscripts g, op, sp, and, ot respectively. The net electrical efficiency of the system, η, is calculated as:

$$\eta_{el} = \frac{W_{net}}{Q_i}. \quad (69)$$

Q_i represents the supplied total heat rate of the biomass burner:

$$Q_i = \dot{m}_f LHV_f. \quad (70)$$

In above equation, Equation (69), $\dot{m}_f$ indicates the biomass feed to the burner and LHV_f represents the lower heating value and calculated as Ref.[178]

TABLE 5 Pine sawdust specifications[175]

Biomass type	Pine sawdust
Moisture content in the fuel (% wt)	10%
Ultimate analysis (% wt dry basis)	
Wc	50.54%
Wh	7.08%
Wo	41.11%
Ws	0.57%

$$LHV_f = HHV_f - 226.04wh - 25.82M_w \quad (71)$$

M_w indicates the moisture content of the used fuel. HHV_f is defined as the higher heating value and similarly to LHV definition, Dulong and Perit presented an equation for its calculation as follows[179]:

$$HHV_f = 338.3wc + 1443\left(wh - \frac{wo}{8}\right) - 94.2ws. \quad (72)$$

In above equation, Equation (71), w is the dry weight percentage and c,o,h, and s represent the presence of carbon, hydrogen, and sulphor, respectively, in the content of the burned biomass. The heating cogeneration efficiency is expressed as:
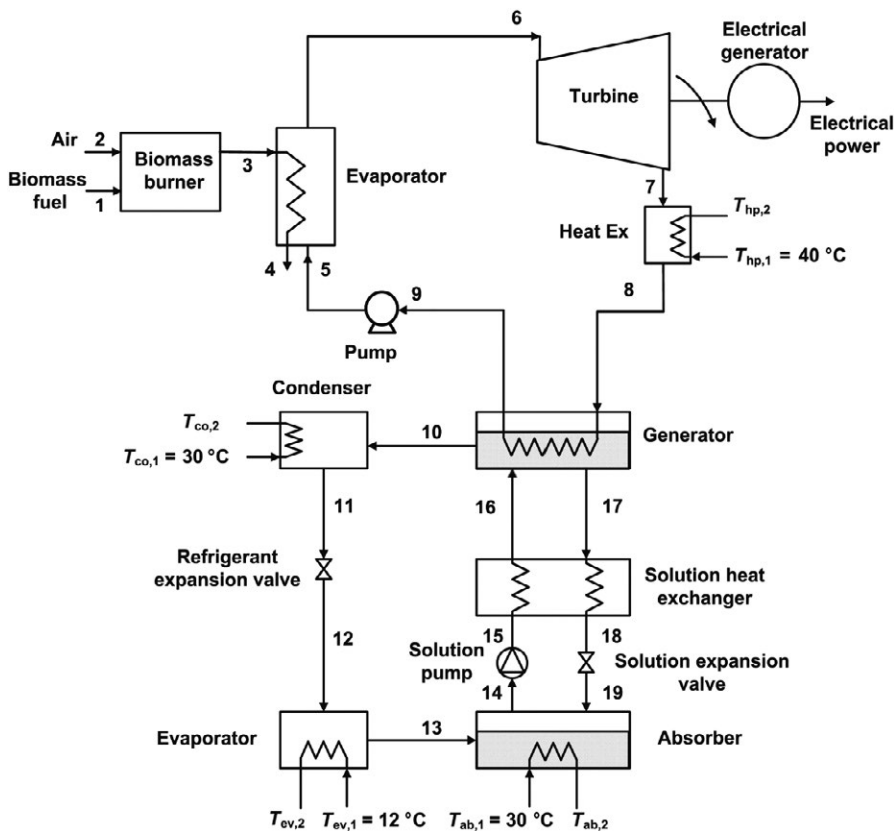
$$\eta_{cog,h} = \frac{Q_h + W_{net}}{Q_i}. \quad (73)$$

FIGURE 10 Schematic design of the tri-generation system[175]

ORC	
Organic cycle pump isentropic efficiency	80%
Organic cycle turbine isentropic efficiency	80%
Effectiveness of the organic cycle evaporator	80%
Mass flow rate	7 kg/s
Baseline pinch point temperature of the ORC evaporator	40 K
Baseline turbine inlet pressure	2000 kPa
Baseline pump inlet temperature	365 K
Electrical motor efficiency	95%
Electrical generator efficiency	95%
Chilling cycle	
Overall heat transfer coefficient of the absorber	75 kW/K
Overall heat transfer coefficient of the condenser	80 kW/K
Overall heat transfer coefficient of the generator	70 kW/K
Overall heat transfer coefficient of the evaporator	95 kW/K
Effectiveness of solution heat exchanger	70%
Ambient condition	
Ambient pressure	101.3 kPa
Ambient temperature	298.15 K

Here, Q_h indicates the heating power and the heating cogeneration is represented by subscript cog, h. The heating power is:

$$Q_h = \dot{m}_{hp} \left(h_{hp,2} - h_{hp,1} \right). \tag{74}$$

In above equation, Equation (73), $\dot{m}_{hp}$ and h are the heating process mass flow rate and specific enthalpy of the water respectively. The subscripts hp,1 and hp,2 indicate the inlet and outlet of the heating process section respectively. The cooling cogeneration efficiency is expressed as:

$$\eta_{cog,c} = \frac{Q_{ev} + W_{net}}{Q_i}. \tag{75}$$

Here, the cooling cogeneration and the produced cooling energy through the chilling process in the evaporator are represented via subscripts cog, c, and ev respectively. The evaporator cooling load is calculated as:

$$Q_{ev} = \dot{m}_8 \left(h_9 - h_8 \right) = \dot{m}_{ev} \left(h_{ev,1} - h_{ev,2} \right). \tag{76}$$

Here, $h_{ev,1}$ and $h_{ev,2}$ indicate the inlet and outlet specific enthalpy of the cooling evaporator respectively.

In overall, the tri-generation system efficiency is expressed as:

$$\eta_{tri} = \frac{Q_{ev} + Q_h + W_{net}}{Q_i}. \tag{77}$$
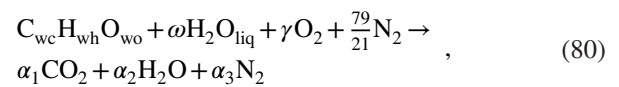
The electrical to heating ratio is stated as:

$$r_{el,h} = \frac{W_{net}}{Q_h}. \tag{78}$$

The electrical to cooling ratio is expressed as:

$$r_{el,c} = \frac{W_{net}}{Q_{ev}}. \tag{79}$$

2.4.2 | Biomass burner

The major part of the introduced tri-generation system is the biomass burner. Hence, its modeling is discussed in detail here. The feeding biomass chemical combustion equation with air and also regarding the assumed complete combustion is:

$$\begin{aligned} &C_{wc}H_{wh}O_{wo} + \omega H_2O_{liq} + \gamma O_2 + \frac{79}{21}N_2 \rightarrow \\ &\alpha_1 CO_2 + \alpha_2 H_2O + \alpha_3 N_2 \end{aligned}, \tag{80}$$

where wh, wc, wo, and ws indicate the dry-weight percentage of hydrogen, carbon, oxygen, and sulphur, respectively, in the content of the feeding biomass which its specification are expressed in Table 1. In addition, u is the biomass moisture content factor in the chemical reaction and can be calculated as:

$$\omega = \frac{M_w M_{CHO}}{1 - M_w M_{H_2O}}. \tag{81}$$

M_w refers to the biomass moisture content. The biomass molar flow rate of the biomass calculated as:

$$n_{CHO} = \frac{\dot{m}_{biomass}}{M_{CHO}} \times 1000 \ (mole/S). \tag{82}$$

M_{CHO} represents the biomass molecular weight. The right-hand side coefficients of Equation (79), can be obtained by writing elements balances as demonstrated in the following:

$$\alpha_1 = wc \tag{83}$$

$$\alpha_2 = \frac{wc + \omega}{2} \tag{84}$$

$$\alpha_3 = \frac{79}{21}\gamma \tag{85}$$

$$\gamma = \frac{2\alpha_1 + \alpha_2 - \omega - wo}{2}. \tag{86}$$

The enthalpy balance between the inlet and outlet of the biomass burner should be written in order to obtain the burner flame temperature. The enthalpy balance is written as:

$$\bar{h}_{CHO,1} + \omega \bar{h}_{H_2O,1} + \gamma \bar{h}_{O_2,2} + \frac{79}{21} \gamma \bar{h}_{N_2,2}$$
$$= \alpha_1 \bar{h}_{CO_2,3} + \alpha_2 \bar{h}_{H_2O,3} + \frac{79}{21} \gamma \bar{h}_{N_2,3}. \quad (87)$$

In this balance, $\bar{h}_{CHO,1}$ is not known. Therefore, it can be obtained by employing the following equation:

$$\bar{h}_{CHO,1} = wc\bar{h}_{CO_2,1} + \frac{wh}{2}\bar{h}_{H_2O,1} + HHV_{biomass}M_{CHO}. \quad (88)$$

The total enthalpy at state 3 can be obtained by using Equation (89):

$$H_3 = n_{CO_2,3}\bar{h}_{CO_2,3} + n_{H_2O,3}\bar{h}_{H_2O,3} + n_{N_2,3}\bar{h}_{N_2,3}. \quad (89)$$

Similar to state 3, the total enthalpy at state 4 can be calculated as:

$$H_4 = n_{CO_2,4}\bar{h}_{CO_2,4} + n_{H_2O,4}\bar{h}_{H_2O,4} + n_{N_2,4}\bar{h}_{N_2,4}. \quad (90)$$

The evaporator pinch point temperature is stated as[180]:

$$T_{pp} = T_4 - T_5. \quad (91)$$

2.4.3 | Exergy analysis

Exergy destruction plays a significant role in exergy analysis. It is demonstrated the lost potential work that is wasted as a result of irreversibility. The exergy destruction rate of a specific control volume under steady-state condition is calculated as:

$$Ex_d = \sum_j \left(1 - \frac{T_0}{T_j}\right)Q_j - W_{cv} + \sum_i m_i ex_i - \sum_e m_e ex_e. \quad (92)$$

Here, T, ex, and Ex_d indicate temperature, exergy per mass flow rate, and exergy destruction rate respectively. The subscript j indicates the property value at state j and the subscript 0 is the ambient property value. The inlet and outlet of the defined control volume is shown by subscripts i and e respectively. The total exergy rate is stated as:

$$ex_{total} = ex^{PH} + ex^{CH}. \quad (93)$$

In above equation, Equation (93), ex^{PH} is defined as the physical exergy per mass flowrate at a given state and obtained as:

$$ex^{PH} = (h - h_0) - T_0(s - s_0) + \frac{V^2 - V_0^2}{2} + g(z - z_0). \quad (94)$$

Here, enthalpy per unit mass, entropy per unit mass, velocity, elevation, and gravity are represented by h, s, V, z, and g respectively. In this study, it is assumed that there is no change

in the velocity and elevation during the process. Thus, their related terms in physical exergy calculation are neglected.

For an ideal gas, the chemical exergy of species j is calculated as Ref.[145]

$$ex_j^{CH} = M_j\left(x_j\overline{ex}_j^{CH} + RT_0 x_j \ln(x_j)\right), \quad (95)$$

where M_j represents the species j molecular weight and $\overline{ex}_j^{CH}$ is the corresponding species chemical exergy. Table 6. expressed the standard chemical exergy values of the material used in this analysis. The variables x indicates the molar concentration and R is the universal gas constant. The net electrical exergy efficiency is expressed as:

$$\eta_{ex,el} = \frac{\dot{W}_{net}}{\dot{Ex}_f}. \quad (96)$$

Ex_f is defined as the fuel (biomass) chemical exergy and obtained as:

$$Ex_f = n_{CHO}.\beta.LHV_f.\left(\frac{M_{CHO}}{1000}\right). \quad (97)$$

β indicates the chemical-exergy coefficient. This coefficient is defined for solid hydrocarbons fuel (for O/C < 2) and can be calculated by using the following correlation[181]:

$$\beta = \frac{1.044 + 0.016\left(\frac{wh}{wc}\right) - 0.3493\left(\frac{wo}{wc}\right)\left(1 + 0.0531\left(\frac{wh}{wc}\right)\right)}{1 - 0.4124\left(\frac{wo}{wc}\right)}. \quad (98)$$

The cooling cogeneration exergy efficiency is calculated as:

$$\eta_{ex,cog,c} = \frac{W_{net} + \left(1 - \left(\frac{T_0}{T_{ev}}\right)\right)Q_{ev}}{Ex_f}. \quad (99)$$

The exergy efficiency of the heating cogeneration is expressed as:

$$\eta_{ex,cog,h} = \frac{W_{net} + \left(1 - \left(\frac{T_0}{T_{hp}}\right)\right)Q_h}{Ex_f}. \quad (100)$$

Here, the subscript hp is the heating-process heat exchanger. The exergy efficiency of the tri-generation system is calculated as:

$$\eta_{ex,tri} = \frac{W_{net} + \left(1 - \left(\frac{T_0}{T_{hp}}\right)\right)Q_h + \left(1 - \left(\frac{T_0}{T_{ev}}\right)\right)Q_{ev}}{Ex_f}. \quad (101)$$

In above equation, the subscript tri refers to tri-generation system.

TABLE 7 Energy, exergy, and economic analyses for Coal-fired power plant

Refs.	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Discoveries and achievements
[34]	210	○	●	○	The highest exergy destruction took place in the boiler.
[52]	200	●	●	○	Condenser had the maximum amount of energy waste, whereas the boiler had the highest amount of exergy destruction
[57]	10	●	●	○	Valuable for engineers, researchers, and policy makers to utilize energy and exergy efficiencies in their designing and plans.
[58]	232.6	○	●	●	The reduction in the amount of exergy destruction can be achieved by surging in the values of the thermodynamic parameters of the operating fluid supplied to the turbine and reducing the temperature differences of net heaters.
[68]	600	○	●	○	Boiler had the highest amount of exergy loss.
[196]	300	○	●	○	The highest exergy destruction occurred in boiler.
[71]	422	○	●	○	The highest exergy destruction occurred in boiler.
[73]	50	●	●	○	Maximum amounts of energy and exergy losses belonged to condenser and combustor respectively
[74]	240	○	●	○	The highest exergy destruction occurred in boiler.
[33]	66	●	●	○	The highest amount of exergy loss occurred in condenser.Energy losses are not significant due to its low quantity based on exergy analysis.
[75]	250	●	●	●	The highest amount of energy losses occurred in condenser and boiler respectively.The highest amount of exergy destruction occurred in boiler.Exergy destruction cost in boiler and turbine were more than the other parts of the system.
[77]	500	●	●	○	Exergy–economy driven maintenance scheduling and performance guarantee test procedures were formulated.
[78]	660	○	●	○	Comparison between ultra-supercritical and subcritical coal-fired power plants is carried out.
[82]	800	○	●	○	The exergy efficiency of conventional system was higher than the Oxy-combustion system.
[93]	300	○	●	●	Thermo-economic approach was applied for analyzing exergy cost of plant. Malfunction analysis was presented in this study.
[98]	500	●	●	○	Comparison between coal-fired power plant and nuclear electrical generation system was done by applying energy and exergy analyses.
[14]	32	●	●	○	Boiler and turbine had the highest amount of exergy losses in the system.
[99]	315	●	●	○	The major portion of energy losses occurred in condenser, while the highest amount of exergy losses occurred in turbine.
[100]	500	●	●	○	Part load working condition led to lower energy efficiency because of higher energy rejection relative to net output, and part load low exergy efficiency was due to higher exergy destruction relative to net output
[123]	210, 150, 160, 150, 157,360, 210, 165, 160.9	●	●	○	Nine power plants were analyzed and compared and the results help engineers to enhance performance of plant and components as well.
[167]	7.7	●	●	○	Fluidized bed coal combustor had the highest irreversibilities based on obtained results.
[197]	600	○	●	○	Oxy-combustion boiler had higher efficiency in comparison with the conventional one.
[198]	1100	○	●	●	An optimization was implemented on a large-scale coal-fired power plant based on thermodynamic and economic approaches.

(Continues)

TABLE 7 (Continued)

Refs.	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Discoveries and achievements
[199]	660	●	●	○	Linking of artificial neural network and genetic algorithm was employed for optimizing power plant thermodynamically.
[200]	348.5	●	●	○	The highest amount of energy losses and exergy destruction occurred in condenser and boiler respectively.
[37]	300	●	●	○	Two power plants with the same capacities were compared. Results depicts that the highest amount of energy losses occurred in condenser.
[201]	110	●	●	○	It is concluded that energy losses in the condenser was not significant due to its low quantity. In addition, the highest amount of irreversibilities occurred in boiler.
[202]	150	●	●	●	The highest and lowest amount of exergy losses occurred in boiler and condenser respectively.
[203]	300	●	●	○	Energy and exergy losses mostly were taken place in condenser and boiler respectively
[204]	660	●	●	○	It was observed that there were no energy losses in combustion, but the highest amount of exergy destruction occurred in boiler.
[205]	1000	○	●	○	Endogenous exergy destruction of an equipment by itself was much larger than that caused by system structure. It was necessary for improving equipment thermal performance to decrease endogenous exergy destruction. Then, external system structure must be optimized to reduce exergy destruction.
[206]	1000	○	○	●	Economic performance of power boosting mode was more favorable than that of fuel saving mode due to the higher share of coal exergy. Based on thermodynamic approach, fuel saving mode was better which was attributed to the greater net power output of solar and efficiency of net power generation. The mode of fuel saving was more feasible using solar energy more efficiently.
[207]	160	○	●	●	Boiler and condenser play important role for enhancing of performance based on exergy analysis.
[208]	250	○	○	●	In this study, repowering for an old 250 MW coal-based power plant through integration of MCFC and carbon capture units was investigated based on thermo-economic approach. The repowering scheme led to enhancement of net output (by 27%) and efficiency of the plant (by 1.1%). The COE of the repowered plant became 82 $/MWh which was 46% more than the existing plant.
[209]	330	●	●	○	This paper gives the theoretically and actually correlation of the solar–to-power efficiency with the exergy destruction of solar hybridization process. The derived explicit expressions explain the reason of the solar-to-power efficiency of hybrid system is superior over that of solar-only power system. The effects of three key parameters on the thermal performances including solar irradiation, incident angle and turbine load are revealed by applying the derived equations into a hybrid system with 330 MW coal-fired power plant. At a given turbine load, the net solar-to-electricity efficiency has a peak value. The net solar-to-electricity efficiency firstly keeps constant, and then decreases by surging in incident angle.

2.4.4 | Literature

Cogeneration and trigeneration systems are considered as one of the most important parts of energy system in different countries. Additionally, these systems are one of the most sustainable energies based on energy conservation and environmental aspects. Exergy analysis is applied in several researches in order to enhance these systems' efficiencies.

TABLE 8　Energy, exergy, and economic analyses for natural-gas-fired power plant

Refs.	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Discoveries and achievements
[110]	150	○	●	○	One of the main reasons for exergy destruction was chemical reaction in combustion process.
[112]	146.2	●	●	○	Combustor was the main source of exergy destruction.
[114]	0.1	●	●	○	The performance of the plant for three sets of working parameters was analyzed and a trade-off in the working condition was obtained.
[115]	—	●	●	○	Intercooled gas turbine and basic gas turbine are compared and it is observed that intercooled gas turbine has higher efficiency and lower exergy destruction.
[116]	—	○	●	●	The highest amount of exergy destruction occurred in combustion chamber.
[117]	—	○	●	○	Combustion chamber had the lowest exergy efficiency among the components.
[119]	—	○	●	●	It is observed that reference temperature, boiler, and condenser efficiency have effects on performance.
[120]	123.4	●	●	●	First and second law efficiencies were affected by inlet fogging system.
[121]	20	●	●	○	The highest amount of exergy destruction occurred in boiler.
[122]	53	●	●	○	The highest amount of exergy losses is taken place in combustion process.
[144]	435	●	●	●	A multiobjective optimization is implemented for obtaining the most appropriate design variables.
[210]	8,10,12,14	○	●	●	A general model (sugar production processes) was developed based on data provided by a real plant, and exergy analysis was carried out. Improvement of performance indicators was achieved through thermo-economic analysis. Unit cost for the turbine power plant was obtained and equal to 3.142 [$/kW].
[211]	—	○	●	○	Energy and exergy efficiency can be enhanced by doing the below recommendations:1. Reducing the inlet temperature which leads to both consuming lower power in compressor and having less amount of exergy destruction.2. Monitoring fuel air ratio in the combustion chamber.
[212]	1000	○	●	●	NSGA-II, MOPSO, and MOEA-D algorithms are applied for analyzing and optimizing of the system based on exergy and exergoeconomic methods. Total cost rate and exergy efficiency are considered as objective functions. In Pareto solution, the middle point was considered as the optimal solution, which had the minimum total cost rate (1.922 US$/s).This amount is 30% and 6.2% less than MOPSO algorithm and MOEA-D algorithm respectively. Moreover, in the NSGA-II algorithm, the exergy efficiency was obtained and equal to 55.1% which was 12% and 10% greater than MOPSO and MOEA-D algorithms respectively.
[213]	—	●	●	○	The power, power density, exergy efficiency, and ECOP increase, while the exergy destruction decreases by increasing equivalence ratio. The EFECPOD increases to a specified value and begins to decline by increasing equivalence ratio. All performance characteristics diminish by increasing of pressure ratios at lower values of equivalence ratios, but they increase by surging in pressure ratios at higher equivalence ratios.

TABLE 9 Energy, exergy, and economic analyses for combined cycle power plant

Refs.	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Discoveries and achievements
[47]	—	○	●	○	50% of exergy destruction in the reheat combined Brayton/Rankine power cycle occurred in combustion chamber.
[154]	—	○	●	○	Based on conventional and advanced exergetic analyses, the highest amount of exergy destruction occurred in combustion chamber.
[155]	—	●	●	○	In an integrated gasification combined cycle power plant, the efficiency was maximized with respect to the optimum pressure ratio for a specified temperature ratio. The highest amount of exergy destruction occurred in gasification process.
[156]	—	●	●	○	Integration of the reforming process and the combined cycle has been investigated for a gas-turbine combined-cycle power plant.
[157]	420	○	●	○	The sensitivity analysis of exergy destruction for various components is assessed.
[158]	—	○	●	○	In combined cycle power plants, the thermal and exergy analyses of heat recovery steam generator have been investigated for various operating conditions with respect to variation of loads and ambient temperature based on the performance test data at diverse operating conditions.
[108]	—	○	●	○	In this study, a heat recovery steam generator utilized at CCPPs is modeled and validated
[161]	—	○	●	○	Integrating of a conventional gas turbine plant with a solid oxide fuel cell increased the efficiency of the cycle by twofold.
[162]	—	○	●	○	In a combined reheat regenerative steam turbine-based power cycle and water–LiBr vapor absorption refrigeration system, it was observed that the highest irreversibility portion belonged to the cooling tower.
[163]	—	●	●	●	A biomass integrated postfiring CCPP was analyzed by applying energy, exergy, and exergoeconomic methods.
[164]	—	○	●	○	Influences of compressor and gas turbine efficiencies on both exergy efficiency and optimal exergy output rate were investigated for a combined cooling, heating, and power plant.
[39]	—	○	●	○	A natural-gas-fired combined cycle power generation system was analyzed by exergy method in order to assess the effects of various factors on the exergetic performance.
[165]	—	●	●	○	Exergy and energy analyses were done comprehensively for an integrated solar combined cycle system by utilizing design plant data
[166]	—	○	●	●	The exergoeconomic assessment of an externally fired CCPP was conducted and avoidable and unavoidable exergy destructions as well as investment costs were determined for each element.
[168]	—	○	●	●	An approach was proposed for the working parameters optimization of a heat recovery steam generator in order to enhance the efficiency.
[60]	—	○	●	○	Exergy analysis and the effects of inlet temperature of heat recovery steam generator on the steam cycle efficiency were investigated for a CCPP.
[190]	—	●	●	○	The highest amount of exergy destruction occurred in the combustor.
[132]	420	○	●	○	In a CCPP, it is observed that combustion chamber has the lowest efficiency. Heat recovery steam generator had the second level in term of exergy destruction.
[214]	—	○	●	○	Analysis and optimization are done for a combined triple power cycle by considering important parameters of the system.

(Continues)

TABLE 9 (Continued)

Refs.	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Discoveries and achievements
[215]	—	○	●	○	A novel combined cycle was proposed to generate power and produce cooling simultaneously with a heat source and utilizing mixture of ammonia and water as operational fluids.
[216]	—	○	●	○	Based on exergy analysis, combustion chamber had the highest amount of exergy losses in a combined Brayton/Rankine power cycle
[217]	—	○	●	○	In a combined power and cooling cycle, the highest amount of exergy destructions occurred in absorber, boiler, and turbine.
[218]	—	○	●	○	In a combined cycle gas turbine power plant, the combustion chamber was responsible for the highest amount of exergy destruction.
[219]	—	○	●	○	The comparison of two plants ie a supercritical steam plant and a gas-steam turbine combined cycle have been carried out. Following results have been derived: 1. The highest amount of exergy losses was caused by mixing in the combustor 2. The highest amount of exergy waste occurred in the heat recovery steam generator. 3. The highest amount of exergy losses were because of inefficiencies in the power section.
[220]	—	○	●	●	A combined cycle power plant was investigated based on exergoeconomic approach, and the plant was also modelled thermodynamically.
[221]	—	○	●	●	A review including the exergoeconomic analysis and optimization of combined heat and power production has been presented.
[148]	—	●	●	○	A CCPP has been analyzed by applying energy and exergy concepts.
[222]	—	●	●	○	Energy and exergy analyses are conducted for a natural-gas-fired combined cycle power plant, and a solar concentrator aided natural-gas-fired combined cycle power plant was used to assess their performance.
[223]	—	○	●	○	In this study, the efficiency of a combined cycle working with an intercooled combustion-turbine was maximized.

Efficiency analysis plays an important role for designing process of cogeneration based district energy system.[182] Alsairafi et al[183] analyzed cogeneration power with a MED desalination unit based on exergy analysis. Various working conditions were considered in this study. Results showed that exergy destruction was not influenced by number of stages, capacity of desalination system, top turbine temperature, and temperature of cooling water. Both exergy destruction, including avoidable and unavoidable, in a cogeneration unit can be simply approximated.[184,185] Bilgen et al[186] applied second law of thermodynamics for determining both chemical and physical exergies. In addition, exergy destruction of the system was calculated. Results showed that for all the steam inlet conditions in cogeneration power plants utilized in sugar industries, higher pressure and temperature of steam generation led to obtaining lower exergy losses and exergetic efficiency enhancement.[107] Saidi et al[187] conducted a study on a 5 kW polymer electrolyte fuel cell with cogeneration application and applied exergy approach for optimization of the system. Kamate et al[188] analyzed a 44-MW bagasse-based cogeneration system of a sugar mill based on energy and exergy concepts. In this study, results showed that the boiler was the main reason for inefficiency of the plant. Both energy and exergy efficiencies have been applied to assess performance of a combustion gas turbine cogeneration system with reheat.[189] Bilgen[46] analyzed and simulated gas turbine-based cogeneration plants using exergy analysis. Energy and exergy analyses have been performed on the other systems ie combined heating, cooling and power generation in order to evaluate their performance.[190] In a cement plant, an optimization parameter was employed for obtaining the maximum exergy efficiency of the single flash steam cycle, dual-pressure steam cycle, organic Rankine cycle and the Kalina cycle using a nontraditional optimization technique.[191] Bayrak et al[192] analyzed an actual diesel engine-based cogeneration system by applying exergy method.

The utilization of hybrid systems, which use both biomass and solar energy, has been developed in recent years. Various analysis including energy, exergy and economic were applied in cogeneration and trigeneration hybrid system.[193] A novel electricity heating cogeneration system was studied based on

TABLE 10 Energy, exergy, and economic analyses for cogeneration and trigeneration systems

Refs.	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Discoveries and achievements
[80]	—	○	●	○	In an organic Rankine cycle working with different operating fluids, the exergy topological approach was applied for presenting a quantitative approximation of the exergy destruction.
[81]	—	○	●	○	Exergy analysis has been employed in micro-organic Rankine power cycles for a small scale solar driven reverse osmosis desalination system.
[97]	—	●	●	○	A computer simulation of a Kalina cycle coupled with a coal-fired steam power plant was employed in order to find the optimum operating conditions of the Kalina cycle.
[105]	—	○	●	○	Energy and exergy analyses were employed for analyzing of Kalina cycle system with various mass fraction ammonia-water mixture.
[160]	—	○	●	○	An integrated organic Rankine cycle is assessed based on exergy concept, and it was observed that the heating-cogeneration and trigeneration cases were less sensitive to the considered pressure and temperature changes in comparison with the electrical power and cooling-cogeneration cases.
[182]	—	●	●	○	A cogeneration-based district energy system was analyzed by both energy and exergy considerations. The exergy efficiencies were typically more meaningful for explaining system behavior in comparison with the energy efficiencies.
[185]	—	○	●	○	An advanced combined cogeneration plant ie a coal gasification and split Rankine combined cogeneration plant was analyzed.
[186]	—	○	●	○	Second law analysis was conducted for finding both chemical and physical exergies and exergy destruction of a cogeneration system.
[107]	—	●	●	○	Exergy analysis of a heat-matched bagasse-based cogeneration plant was employed to assess both overall and components' efficiencies and find and evaluate the thermodynamic losses.
[187]	0.05	○	●	○	Design and exergy optimization approach of a power output polymer electrolyte fuel cell with a cogeneration application (with 5 kW capacity) was analyzed to have highest efficiency and lowest generation of entropy. It was concluded that temperature and voltage of fuel cell should be as high as possible.
[188]	44	●	●	○	A bagasse-based cogeneration plant was analyzed based on energy and exergy methods for evaluating thermodynamic efficiencies and losses.
[189]	—	●	●	○	Energetic and exergetic efficiencies were defined for a combustion gas turbine cogeneration system with reheat.
[46]	—	○	●	○	Two cogeneration cycles, one of them consisted of gas turbine, and another one had both gas and steam turbines, were analyzed based on exergy analysis.
[191]	—	○	●	○	The exergy analysis for cogeneration in cement plant was conducted by applying genetic algorithms for obtaining the highest amount of exergy efficiency. In comparison with other systems, the Kalina cycle had enough capability to reach to the best performance in cement plant.
[192]	11.52	●	●	○	An actual Diesel engine-based cogeneration plant was analyzed by applying exergy method, and it was concluded that combustion process, heat losses from the engines and friction were the main sources of exergy destruction.
[224]	1.03	●	●	○	Employing primary energy savings and exergy destruction analyses to compare decentralized power production through cogeneration/trigeneration systems as well as centralized thermal plants was investigated. It was concluded that both methods achieved the same results if the thermal efficiency indicator was used to compare the methods. The analysis also revealed that trigeneration systems with the same energy input were comparable with quite different thermal efficiency centralized thermal plants. Case 1 was comparable to a 53% thermal efficiency power plant and case 2 was comparable to a 77% thermal efficiency power plant.
[225]	1	○	●	●	11 industrial cogeneration systems were developed. They commented that following the EU Directive 2004/08/EC and the commission decision of 21 December 2006, it was established that high efficiency cogeneration systems higher than 1 MW capacity should have a 10% primary energy savings (PES) compared with electricity production in centralized thermal plants with a thermal efficiency of 48.6% and heat production with an efficiency of 90%.
[193]		●	●	●	3-E analysis of a cogeneration and trigeneration ORC–VCC hybrid system utilizing biomass fuel and solar power was performed. The aforementioned system generated 1.4 kWe with cooling of 5 kWth of 53.5 kWth respectively. Energetic and exergetic efficiencies were obtained and were equal to 5.54% and 7.56% respectively. Furthermore, economic analysis revealed that IRR and base case payback period were approximately 12% and 7 years respectively.

(Continues)

TABLE 10 (Continued)

Refs.	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Discoveries and achievements
[226]		●	●	●	Energy, exergy, and thermoeconomic analyses were performed on a CCHP system. It was concluded that applying the first and second laws of thermodynamics in conjunction with economic analysis at the same time creates a reliable tool for analyzing CCHP systems.
[227]		●	●	○	CHP, CCHP, and CCP systems were investigated using exergy analysis. Exergy efficiency of all the above-mentioned integrated systems was higher compared with the single generation system.
[228]		●	●	○	A novel trigeneration system using solar energy and biomass was analyzed by exergy method. The maximum exergy destruction took place in the gasifier.
[229]		●	●	○	A biomass CCHP system was investigated using energy and exergy analyses. The analyses showed that largest destruction occurred in the gasification system, accounting for more than 70% of the total losses.
[230]		●	●	●	3-E analysis of a new combined cooling, heating, and power (CCHP) system was carried out. The system had a high exergy efficiency and fuel energy saving ratio. Moreover, the economic analysis showed that the system was affordable in practice.
[231]		●	●	○	An energy and exergy analyses has been performed on an innovative CCHP driven by solar energy. On the condition of utilizing a double effect absorption refrigeration system, the amount coling power increases up to 48.5%.
[232]		●	○	○	Various practical combined configurations have been proposed for cogeneration of power and fresh water/cooling. As the results indicated, configurations which use stream extraction on the condition of lower pressure and temperature are more efficient.
[233]		○	●	●	A new combined system including CCHP-ORC, Solar-ORC has been introduced. According to the results, the best economic performance is associated with Solar-ORC system.
[234]		●	●	○	A combined system has been provided for producing hydrogen with the help of geothermal energy. It has been concluded that the exergy and energy efficiencies are 44.27% and 39.46% respectively.
[235]		●	●	●	Energy, exergy, and economic analyses of a biomass gasification founded on multigeneration have been performed.
[236]		●	●	●	Investigations on an integrated system including water heater, organic Rankine cycle, a reverse osmosis desalination unit, photovoltaic solar collectors, and a single effect absorption chiller have been carried out.
[237]		●	●	●	Analysis of an innovative trigeneration system working with geothermal heat source and LNG has been presented. According to the results, thermal and exergy efficiencies the system were observed to be 85.92% and 18.52% respectively.
[238]		●	●	●	Study of centralized cold generation in trigeneration system combined with steam-powered absorption chillers has been performed.
[239]		●	●	●	A small-scale trigeneration system to produce fresh water and electricity by utilizing geothermal energy has been investigated. The fresh water production capacity of proposed system is 0.662 kg/s.
[240]		●	●	●	For generating power and hydrogen, a modification of organic Rankine cycle (ORC) with a regeneration has been utilized. As indicated in the results, the highest energy and exergy efficiencies belong to R245fa, which are 3.511% and 67.58% respectively.

thermodynamic and an analysis was performed for both specific and variable conditions.[194] An optimization parameter for each cogeneration system was obtained by utilizing genetic algorithm for reaching to the highest amount of exergy efficiency. The optimal performances were compared under the same conditions for different cogeneration systems.[191]

Mahmoudi [195] conducted a study on a combined recompression supercritical carbon dicoxide/ORC cycle and applied exergy and exergoeconomic methods for evaluating of aforementioned cycle. Results indicated that exergy efficiency of sCO2 cycle enhanced by approximately 11.7%, and the total cost of product unit decreased about 5.7%.

Furthermore, based on the results, the highest exergy efficiency and the minimum cost of product unit for the cycle were achieved in the case of utilizing isobutane and RC318 as the ORC operating fluid respectively. The ORC had low working pressure and cost because of its simplicity.

3 | RESULTS AND DISCUSSION

In this study, several valuable and authentic papers have been scrutinized based on 3-E analysis for all of the thermal power plants. The obtained results of reviewed papers along with

plants' capacities are congregated presented in Tables 7-10 precisely. In the reviewed papers, several analyses have been conducted including exergy, energy, economic, and exergo-economic analyses. In order to get better insight, these studies are represented as well. Thermal power plants are categorized in four groups: coal-fired power plant, natural-gas-fired power plant, combined-cycle power plant, and cogeneration system.

Based on the summaries of the studies, which are represented in the above table, in the most of the cases, the highest exergy destruction occurs in boiler and combustion chamber. It can be attributed combustion process, which has high exergy destruction, and heat transfer in high temperature difference. In addition, it can be concluded that using exergy analysis results in better insight into the plant defects and its potential to achieve higher efficiencies and more favorable performance compared with energy analysis. Integrating power plants with other systems such as fuel cells or desalination units will lead to enhancement in both energy and exergy efficiencies since it prevents heat losses. The performance of power plants integrated with other systems depend on several factors such as working condition, efficiency of each component and etc. In order to enhance the efficiencies, it is necessary to figure out the components which have inappropriate performance and improve their efficiency. Moreover, finding the optimal working condition is another approach to achieve higher efficiencies.

4 | CONCLUSIONS

In this paper, various studies conducted on thermal power plants have been reviewed and derived key results are presented. 3-E analysis, including energy, exergy, and economic analyses, has been employed for analyzing of power plants. In coal-fired power plants, numerous researches have been carried out for thermodynamic analysis of Rankine cycle. The highest level of energy losses occurred in the condenser and boiler respectively. In addition, it can be concluded that the cost of exergy destruction in the boiler and turbine is more than the other parts. In the case of natural-gas-fired power plant, the combustor is considered as the main source of exergy destruction. In a CCPP, the maximum amount of exergy destruction has been taken place in combustion chamber based on obtained results from exergy analysis. Hitherto, there have not been much focuses and attentions paid to energy and exergy analyses of supercritical, ultra-supercritical, and advanced supercritical cycles. This issue is because of the material that cannot sustain very high pressures and temperatures in the plant. The efficiency of power plants can be enhanced by applying novel methods such as working under supercritical conditions. This magnitude of saving can be derived by operating the power plant with increased efficiency demands through concentrated efforts of

the research community in this realm. In fact, this matter is possible only if the metallurgical scientists significantly progress the development of new material that can withstand higher temperatures and pressures.

NOMENCLATURES

C	Exergetic cost
h	Enthalpy
m	Mass
Q	Heat
S	Entropy
W	Work
Z	Purchase cost
Ex	Exergy
η	Efficiency
LHV	Lower Heating Value

Subscripts:

c	Cold
cog	Cogeneration
cv	Control volume
d	Destruction
ev	Evaporator
h	Hot
hp	Heating process
f	Fuel
p	Product

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