Babylonian Journal of Mechanical Engineering
Vol.2025, **pp**. 68–90
DOI: https://doi.org/10.58496/BJME/2025/005; ISSN: 3006-5410
https://mesopotamian.press/journals/index.php/BJME

Research Article

A Comprehensive Study of Energy, Exergy, Exergoeconomic, and Exergoenvironment Analysis of Combined Cycle Power Plant

Ahmed Sarhan Abdulsitar [1, *], Arkan Fawzi Saeed [2], Hatem Hasan Ismaeel [1]

[1] *Department of Energy Engineering, Technical College of Engineering, Duhok Polytechnic University, Kurdistan Region -Iraq.*
[2] *Department of Mechanical Engineering, College of Engineering, University of Duhok, Kurdistan Region-Iraq.*

ARTICLE INFO

Article History
Received 18 Feb 2025
Revised: 17 Mar 2025
Accepted 15 Apr 2025
Published 15 May 2025

Keywords
CCPP
Energy analysis
Exergy analysis
Exergoeconomic analysis
Exergoenvironment analysis

ABSTRACT

One of the most effective ways to generate electricity in the thermal power plant is with a Combined Cycle Power Plant (CCPP), which uses both gas and steam turbines to their full potential. This research employs energy, exergy, exergoeconomic, and exergoenvironmental analyses to assess the CCPP performance. Energy analysis indicates the plant's overall efficiency, while exergy analysis identifies losses due to system irreversibilities and proposes methods for enhancement. Exergoeconomic analysis, which integrates thermodynamic and economic factors, quantifies the financial impact of exergy losses and identifies cost-effective improvement strategies. Reducing emissions of pollutants and greenhouse gases is possible through the use of exergoenvironmental analysis. The research examines case studies from several CCPPs worldwide, emphasizing how these analytical approaches have led to enhanced performance, reduced costs, and environmental benefits. Finally, the paper provides a thorough foundation for future research and development in this area by emphasizing the significance of integrated analysis in improving the efficiency, economic feasibility, and environmental sustainability of CCPPs..

1. INTRODUCTION

The escalating global demand for energy necessitates the implementation of more appropriate and efficient power generation technologies. Enhancing efficiency and minimizing pollutants are essential considerations in the construction of power-producing plants. CCPPs can be utilized to generate electricity and thermal energy with better efficiency. CCPPs are strategically positioned to address the rising global energy demand, although they can still gain from the optimization of mechanical, electrical, and environmental cycles [1]. The primary objective of the researchers is to achieve higher thermal efficiencies of the CCPPs to 60% using current technologies [2]. There has been widespread pollution as a result of the release of large amounts of waste heat, including emissions from power plants. Therefore, in order to reduce reliance on fossil fuels and other environmental concerns, it is critical to use renewable energy sources and recycle waste heat [3]. In the present era, it is crucial to utilise existing energy resources efficiently. This is due to the escalating global population which is placing excessive demands on energy. Consequently, there is a looming risk of our resources becoming inadequate to satisfy this growing need in the near future. The global power demand increased at a rate of about 6% each year, according to studies [4]. Energy consumption is a crucial indicator of a country's economic success, with electricity production being the primary component of energy usage. Over the past few years, almost 80% of the global electrical supply has been derived from power plants that burn fossil fuels [5]. While fossil fuels have become the dominant source of energy, they have also become a major contributor to air pollution emissions [6].

Nomenclature

		Subscripts	
$\dot{Q}$	Heat transfer (kW)	D	Destruction
T	Temperature (K)	N	Annual total of operating hours for the unit
T_{PZ}	Flame temperature (K)	o	Ambient
P	Pressure (MPa)	i	Interest rate
$\dot{m}$	Mass flow rate (kg/s)	n	Total number of years that the system is operational
$\dot{W}$	Work (kW)		

*Corresponding author. Email: ahmedasarhan33@gmail.com

h	Enthalpy (kJ/kg)	σ	Standard deviation
s	Entropy (kJ/kg. K)	ϕ	Mass or molar fuel-air ratio
$\dot{E}_X$	Exergy (kW)	π	Dimensionless pressure
$\dot{E}_{X_D}$	Exergy destruction (kW)	θ	Dimensionless temperature
$\dot{E}_{X_{ph}}$	Physical exergy (kW)	ψ	Atomic ratio
$\dot{E}_{Xch}$	Chemical exergy (kW)		
$\dot{E}_{X_{mix}}^{ch}$	Mixture of chemical exergy (kW)		
Ex_f	Fuel exergy (kJ/ kg)	**Abbreviations**	
η_{ex}	Exergy efficiency	CCPP	Combined Cycle Power Plant
X	Mole fraction	AC	Air Compressor
R	Gas constant (kJ/kg. K)	CC	Combustion Chamber
ξ	Coefficient of fuel chemical exergy	GT	Gas Turbine
λ	Air-Fuel ratio	HRSG	Heat Recovery Steam Generation
LHV	Lower heating value (kJ/ kg)	ST	Steam Turbine
C_p	Heat capacity at constant pressure (kJ/kg. K)	Cond	Condenser
$\dot{C}$	Cost rate ($/ s)	CRF	Capital Recovery Factor
c	Cost per unit of exergy ($/ MJ)		
Z_k	Component purchase cost ($)		
$\dot{Z}$	Capital cost rate ($/s)		

Figure (1) illustrates a comparison of thermal efficiency among several power facilities. Various power plants have been created, however the majority suffer from low thermodynamic efficiency due to significant heat losses during electricity production. Due to its superior thermal efficiency in comparison to power plants with separate steam and gas turbine cycles, CCPP has received significant focus. The CCPP is a means of optimizing energy resource utilization. Commonly utilized energy sources in CCPP include natural gas, coal, and diesel [7]. Over 70% of CCPP systems utilize a natural gas-fired gas turbine [8]. CCPP consists of two primary co-generation cycles. The first cycle, known as topping, involves a gas turbine generator. The second cycle, known as bottoming, involves a steam turbine generator [9]. Figure (2) shows a simplified diagram of the CCPP. The CCPP is an energy generation system that achieves great efficiency by combining gas and steam turbines to generate electricity. This cutting-edge design utilizes the hot exhaust gasses from the gas turbine to generate steam, which in turn powers a steam turbine to provide extra electricity. CCPPs achieve markedly superior thermal efficiency compared to conventional single-cycle power plants by employing both gas and steam turbines within a single cycle. The first step is the air compressor, which draws in air from the surrounding environment and feeds it into the machine. Afterward, air will continue to enter the combustion chamber (CC), and fuel will be added to increase the energy level. The next step is to feed the combustion gases into the turbine so that they can produce mechanical work. It is very important to generate more thermal systems using the excess heat that is released by the exhaust [10].

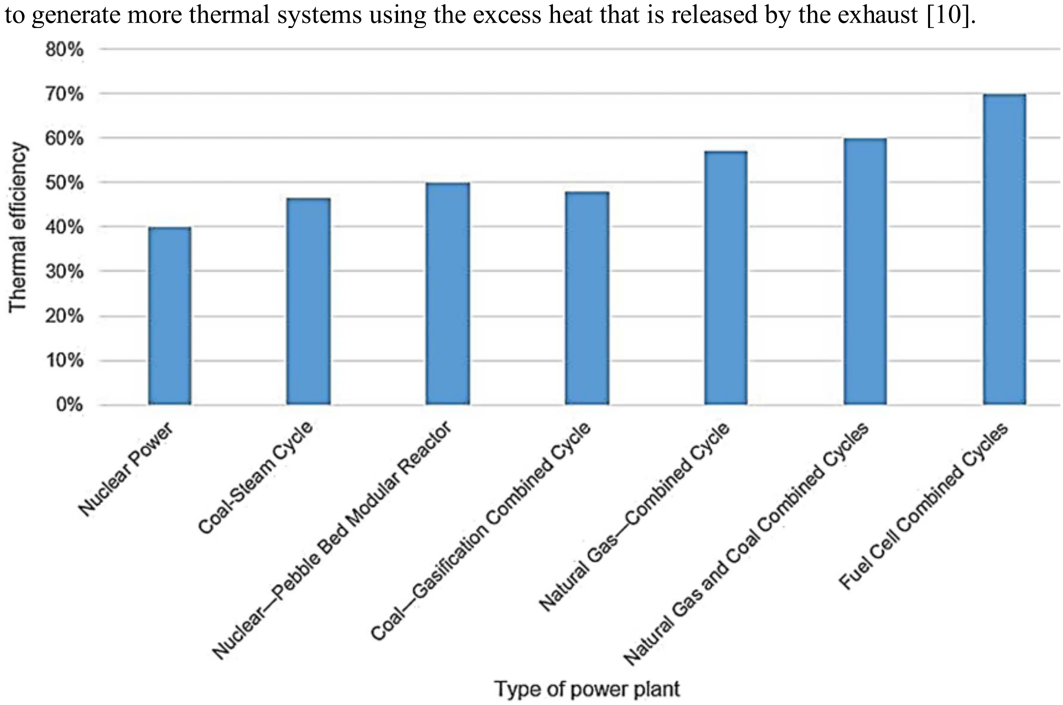


Fig. 1. Thermal efficiency comparison among various power plants [11].

The waste heat from the exhaust gas of a gas turbine is captured and reused in a CCPP using a heat recovery steam generator. The steam produced is then utilized to power a steam turbine, generating more electricity. This process enhances the overall efficiency of the system and reduces pollution. The GT converts the mechanical energy from the combustion of common air and fuel into electrical power [12]. Spark ignition is used to ignite the mixture of air and fuel, and the gas that is burned is then sent to the turbine. Power is produced by the generator when the energy from the burned gases is transmitted to the turbine's rotor blades, which in turn rotate the generator [13]. The GT performance is highly conditional on ambient conditions. Elevation, air temperature, and relative humidity are the three primary factors that often impact ambient conditions [14]. Increasing the Turbine Inlet Temperature (TIT) and compressor pressure ratio successfully improved GT performance [15]. The combustion chamber of a gas turbine is responsible for producing the maximum amount of exergy, which allows the compressor to reduce exergy loss during the cycle by increasing the pressure ratio [16]. The total efficiencies of the plant were significantly improved due to the improved performance of the compressor and turbine. Alterations to the basic gas turbine cycle, particularly the intercooler, regeneration, and reheating procedures, can substantially increase a power plant's ability to generate electricity [17]. More efficient power generation systems that rely on renewable energy sources have lately come to the forefront as a means to lessen the impact on the environment by decreasing fuel consumption [18]. Renewable energy has been the fastest-growing energy source [19]. In an effort to lessen our impact on the environment, a number of studies have concentrated on renewable energy sources [20]. Figure (3) depicts the increase in demand for energy and demonstrates the energy supply from several sources.

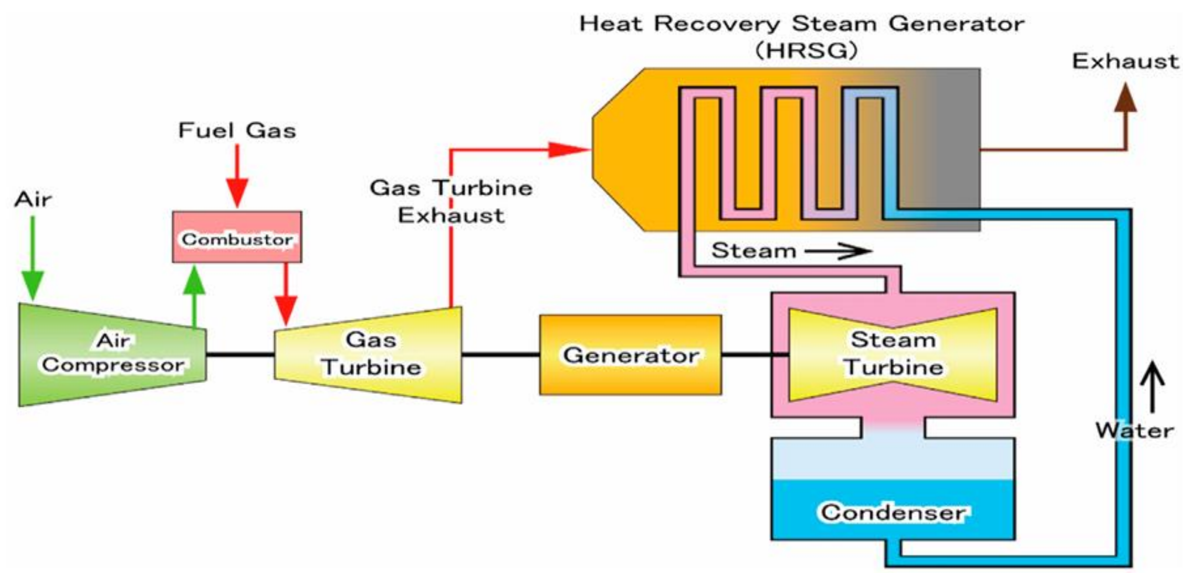


Fig. 2. The diagram illustrating the functioning of the CCPP [21].

Exergy analysis can be used to discover where system losses happen [22]. The exergy analysis, which utilizes the first and second laws of thermodynamics, is a crucial method for examining energy systems. Exergy evaluation is a method that quantifies the efficiency and potential work in CCPP components. Additionally, it allows for the specification of the system's maximum performance [23]. Power plants and energy-consuming equipment can greatly benefit from combining economic and exergy analyses to improve their thermal performance [24]. The primary purpose of analyzing CCPP is to reduce the generation of entropy and irreversibility in the cycle, which eventually improves the efficiency of coupled cycles. The GT inlet temperature and pressure ratio of the topping cycle are the primary factors that significantly impact the CCPP [25].

Mohammad Reza et al. [26] Analyzed the inlet air cooling systems for the GT across different climates utilizing energy, exergy, exergoeconomic, and exergoenvironmental (4E) assessments. The absorption chiller system and the inlet fogging system function best in warm and dry regions, according to the data. The inlet fogging system is not ideal for usage in humid regions due to its lower efficiency. The findings indicate that the optimal cooling solution for urban areas with elevated temperatures is the absorption chiller, which enhances GT net power by 18%. Reducing emissions of nitrogen oxides by 60% is achieved through intake air cooling. Both the input fogging and absorption chiller systems have significant upfront expenses due to the need to purify and transmit water for the fogging system, as well as for the thermal recovery unit and heat exchanger coils for the absorption chiller system. Based on the results, it is not cost-effective to deploy these systems in cold areas. The low installation and maintenance costs of heat pump systems make them the better choice in cold climates. Ersayin and Ozgener [27] analyzed the performance of CCPP based on the principles of the first law and second laws of thermodynamics. The analysis relied on the factual data. Analyzed the parameters and calculated the energy efficiency of plant components. The findings indicated that the energy efficiency was 56% and exergy efficiency was 50.04%. Tajik Mansouri et al. [28] examined the impact of HRSG pressure levels on CCPP performance. The results showed that by increasing the number of pressure levels in the HRSG, the stack gas exergy and the total exergy destruction rate of the entire cycle dropped, while the energy efficiency of the overall system increased. The triple pressure level in the HRSG with a reheater increases the exergy efficiency in CCPP [29]. The study conducted by Kumar and colleagues [30] examined using the principles of thermodynamics, comparing two pressure levels in HRSG. Moreover, a comparison is made between single and dual pressure levels in HRSG. Based on the study, the cycle efficiency and effectiveness of a dual-pressure HRSG are greater than those of a single-pressure HRSG.

Research has been conducted in recent years on the energy, exergy, exergoeconomic, and exergoenvironmental analysis of thermal power plants to optimize performance. To better understand combined cycle power plants, this article compiles and analyses existing research on the subject. This paper goes over the fundamentals of the various combined cycle power plant configurations, how to enhance them, and how to model and simulate them.

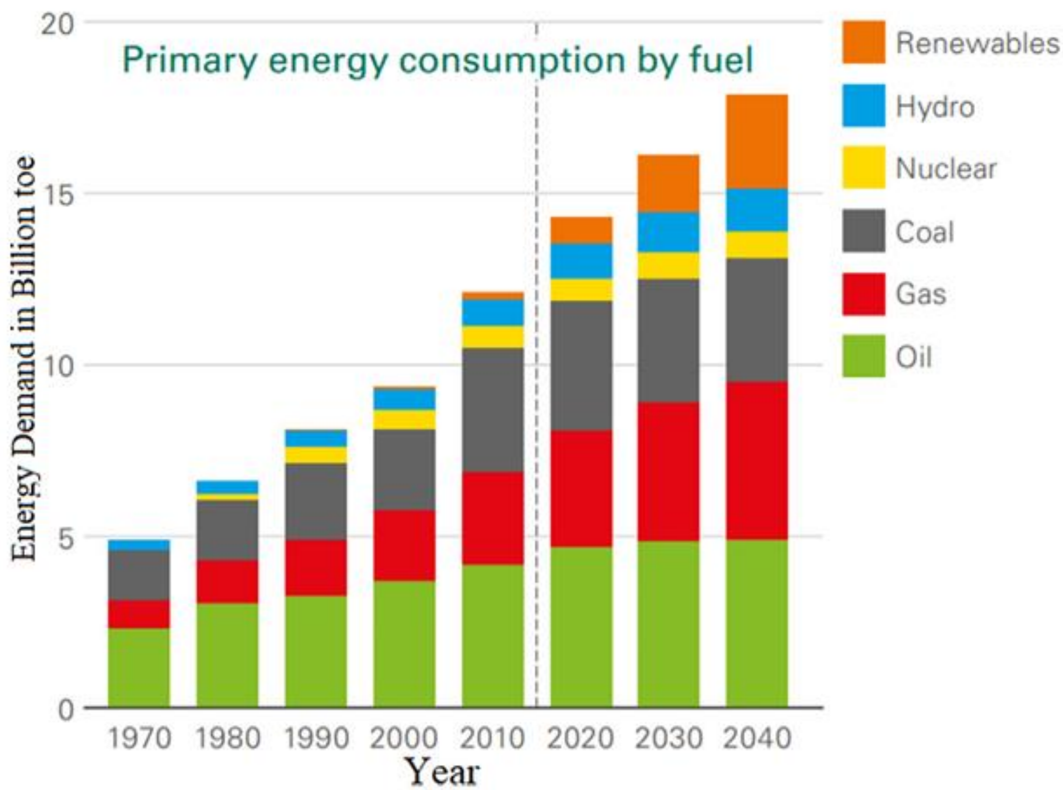
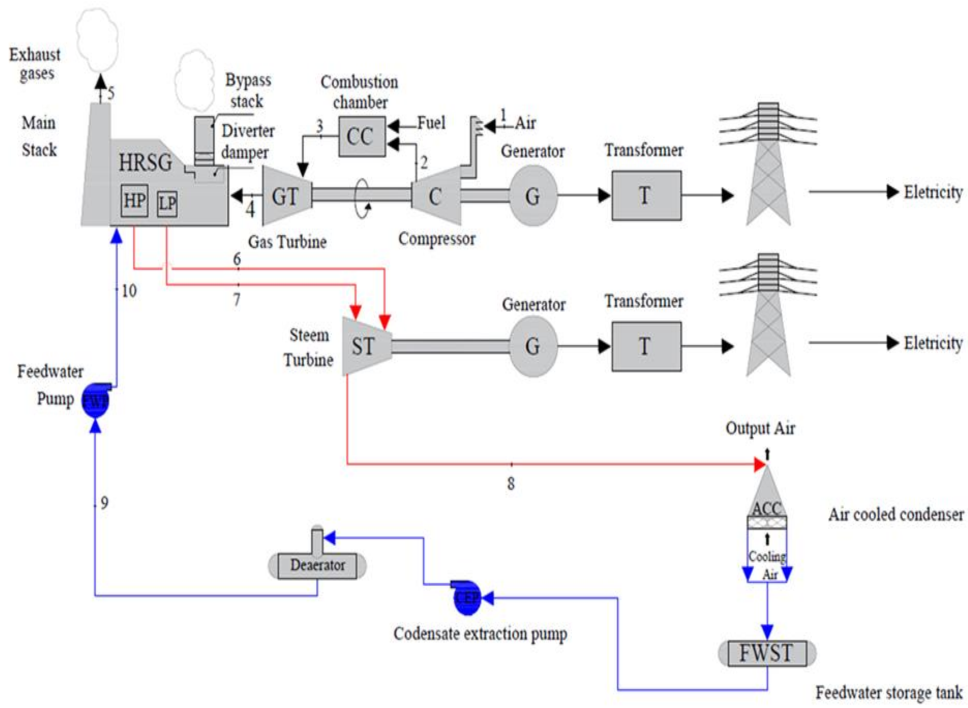


Fig. 3. Diverse fuel sources for fulfilling fundamental energy requirements [31].

2. MODEL ANALYSIS OF COMINED CYCLE POWER PLANT

A more efficient power production system is offered by the CCPP plant, which utilizes cogeneration technology. This technology allows for the simultaneous utilization of electricity and heat from a fuel. The first rule of thermodynamics is commonly used in system energy analysis methodology to analyze the process of energy conversion [32]. When evaluating a power system's efficiency, energy analysis is thought of as the most cost-effective and practical examination. Nonetheless, the subject of advanced thermodynamics, which analyses cycles using energy and exergy and combines the first and second laws of thermodynamics, is gaining more attention [33]. A useful tool for a clear variance between external energy losses and internal irreversibilities is the analysis that uses the exergy approach [34]. Enhancements in the thermal efficiency of power generation units and consumption devices can be substantially realized by integrating exergy analyses with economic assessments [35]. In order to determine the efficacy and ecological imprint of CCPP operations, an exergoenvironmental study integrates the concepts of exergy analysis and environmental impact evaluations. The environmental analysis takes into account the costs associated with pollution flows in addition to the exergetic in thermal systems [36]. CC has high exergy destruction that produces high emissions of nitrogen oxides NO_x and carbon monoxide CO_2. Improving this component's efficiency reduces these emissions.



Point	Details
1	Air enters the compressor
2	Air leaves the compressor
3	Air mixed with fuel
4	Combustion gases leave the gas turbine
5	Exhaust gases
6	Steam generation at high-pressure
7	Steam generation at low-pressure
8	Steam leaves the steam turbine
9	Water leaves the condenser
10	Water leaves the pump

Fig. 4. The sketch of the combined cycle power plant with a capacity of 400MW [37].

2.1. Energy analysis

The energy analysis is a technique that can be used to increase power system efficiency and decrease fuel costs [38]. A crucial method for assessing a system's efficiency, energy analysis is based on the principle of conservation of energy, the first law of thermodynamics [39]. Energy analysis is concerned only with the amount of energy and does not take into consideration its quality. Energy in the form of heat, either added to or removed from a system. Work done by or on the system, such as the rotation of a turbine's shaft, is an example of mechanical energy. Equation 1 can be used to determine the work of the air compressor [40].

$$\dot{W}_{AC} = \dot{m}_a(C_{pa,2}T_2 - C_{pa,1}T_1) \tag{1}$$

where $\dot{W}_{AC}$ is the air compressor work, $\dot{m}_a$ is the air mass flowrate, T_1 is the compressor inlet air temperature, T_2 is the compressor outlet air temperature, $C_{pa,1}$ is the compressor inlet air specific heat, and $C_{pa,2}$ is the compressor outlet air specific heat. The specific heat of air can be calculated according to Equation 2 [41].

$$C_{pa}(T) = 1.04841 - \left(\frac{3.83719 \times T}{10^4}\right) + \left(\frac{9.45378 \times T^2}{10^7}\right) - \left(\frac{5.49031 \times T^3}{10^{10}}\right) + \left(\frac{7.92981 \times T^4}{10^{14}}\right) \tag{2}$$

Equation 3 displays the relationship between the inlet and outlet temperature of the compressor [42].

$$T_2 = T_1\left(1 + \frac{1}{\eta_{AC}}\left(\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right)\right) \tag{3}$$

where η_{AC} is the air compressor efficiency, P_1 is the compressor inlet air pressure, P_2 is the compressor outlet air temperature, and k is the specific heat ratio.

Equation 4 shows the energy balance of the combustion chamber [43].

$$\dot{m}_a C_{pa,2} T_2 + \dot{m}_f LHV + \dot{m}_f C_{pf} T_f = \dot{m}_g C_{pg,3} T_3 \tag{4}$$

where $\dot{m}_f$ is fuel mass flowrate, LHV is the low heating value, C_{pf} is the fuel specific heat, T_f is the fuel temperature, $\dot{m}_g$ is the gas mass flowrate, $C_{pg,3}$ is the specific heat of the gas at inlet of the GT, and T_3 is the inlet gas temperature of the GT.

Equation 5 can be used to determine the combustion chamber efficiency [44].

$$\dot{m}_a C_{pa,2} T_2 + \dot{m}_f LHV + \dot{m}_f C_{pf} T_f = \dot{m}_g C_{pg,3} T_3 + (1 - \eta_{CC})\dot{m}_f LHV \tag{5}$$

$$\dot{m}_g = \dot{m}_f + \dot{m}_a \tag{6}$$

where η_{CC} represents the efficiency of the combustion chamber.

Equation 7 can be used to determine the work of the gas turbine [45].

$$\dot{W}_{GT} = \dot{m}_g (C_{pg,3} T_3 - C_{pg,4} T_4) \tag{7}$$

where $\dot{W}_{GT}$ is the gas turbine work, $C_{pg,4}$ is the specific heat of the gas at the outlet of the GT, and T_4 is the outlet gas temperature of the GT.

The specific heat of gas can be calculated according to Equation 8 [46].

$$C_{pg}(T) = 0.991615 + \left(\frac{6.99703 \times T}{10^5}\right) + \left(\frac{2.7129 \times T^2}{10^7}\right) - \left(\frac{1.22442 \times T^3}{10^{10}}\right) \tag{8}$$

Equation 9 displays the relationship between the inlet and outlet temperature of the gas turbine [47].

$$T_4 = T_3\left(1 - \eta_{GT} - \eta_{GT}\left(\frac{P_3}{P_4}\right)^{\frac{1-k}{k}}\right) \tag{9}$$

where η_{GT} is the gas turbine efficiency, P_3 is the inlet gas pressure of the gas turbine, and P_4 is the outlet gas temperature of the gas turbine.

Equation 10 can be employed to determine gas turbine net power output [48].

$$\dot{W}_{Net} = \dot{W}_{GT} - \dot{W}_{AC} \tag{10}$$

where $\dot{W}_{Net}$ is the net power output of the gas turbine.

Equation 11 displays the energy balance of the heat recovery steam generation [49].

$$\dot{m}_6(h_6 - h_{10}) + \dot{m}_7(h_7 - h_{10}) = \dot{m}_g\left(C_{pg,4} T_4 - C_{pg,5} T_5\right) \tag{11}$$

where $\dot{m}_6$ is the high-pressure steam mass flowrate, h_6 is the enthalpy of the high-pressure steam, where $\dot{m}_7$ is the low-pressure steam mass flowrate, h_7 is the enthalpy of the low-pressure steam, h_{10} is the water enthalpy, $C_{pg,5}$ is the specific heat of the flue gases, and T_5 is the flue gas temperature.

Equation 12 can be employed to determine steam turbine power output [50].

$$\dot{W}_{ST} = \dot{m}_6\, h_6 + \dot{m}_7\, h_7 - \dot{m}_8\, h_8 \tag{12}$$

where $\dot{W}_{ST}$ is the power generation of the ST, $\dot{m}_8$ is the total steam mass flowrate, and h_8 is the enthalpy of outlet steam of the steam turbine.

Equation 13 can be used to calculate the heat transfer in the condenser [51].

$$\dot{Q}_{cond} = \dot{m}_8(h_8 - h_9) \tag{13}$$

where $\dot{Q}_{cond}$ is the condenser heat transfer and h_9 is the enthalpy of outlet water of the condenser.

Equation 14 can be used to calculate the pump work [52].

$$\dot{W}_{pump} = \dot{m}_W(h_{10} - h_9) \tag{14}$$

where $\dot{W}_{pump}$ is the pump work and h_{10} is the enthalpy of outlet water of the pump.

Equation 15 and Equation 16 can be used to determine the thermal efficiency of the gas turbine and combined cycle power plant, respectively [53].

$$\eta_{I,GT} = \frac{\dot{W}_{net,GT}}{\dot{m}_f LHV + \dot{m}_f C_{pf} T_f} \tag{15}$$

$$\eta_{I,CCPP} = \frac{\dot{W}_{net,GT} + \dot{W}_{net,ST}}{\dot{m}_f LHV + \dot{m}_f C_{pf} T_f} \quad (16)$$

Where $\eta_{I,GT}$ is the thermal efficiency of the gas turbine and $\eta_{I,CCPP}$ is the thermal efficiency of the combined cycle power plant.

2.2. Exergy analysis

Exergy analysis has prospered in recent years as an appropriate tool for understanding the methods that improve CCPPs performance [54]. Exergy is characterized in four ways. Out of these four categories, physical and chemical exergy are the ones that are typically taken into account in exergy analyses [55]. Just like in previous thermodynamic studies of power plants, the variables for kinetic exergy and potential exergy are neglected due to the lack of changes in both height and velocity [56], [57], [58]. A system's physical exergy is the amount of exergy caused by its temperature and pressure differences from its environment [59]. Calculated at a specific ambient temperature and pressure, it measures the maximum amount of work that can be extracted from a system as it goes through a physical process until it finds equilibrium with a reference environment. By measuring the usable work potential according to the system's physical state concerning its surroundings, physical exergy aids in comprehending and improving the efficiency of thermodynamic systems. Chemical exergy is the maximum amount of work that a fuel can produce through its chemical reactions until reaches environmental equilibrium [60]. Fuels have a greater chemical exergy than their lower heating values due to that exergy takes into consideration the irreversibilities of combustion as well as the chemical potential of both reactants and products. The exergy balance of the combined cycle power plant can be written as follows [61], [62].

$$\dot{E}_{X_{heat}} - \dot{E}_{X_{work}} + \sum_i \dot{E}_{X_i} - \sum_o \dot{E}_{X_o} - \dot{E}_{X_D} = 0 \quad (17)$$

$$\sum_n \left(1 - \frac{T_o}{T_n}\right) \dot{Q}_n - \dot{W} + \sum_i \dot{E}_{X_i} - \sum_o \dot{E}_{X_o} - \dot{E}_{X_D} = 0 \quad (18)$$

Where $\dot{E}_{X_{heat}}$ is the exergy transfer by the heat, $\dot{E}_{X_{work}}$ is the exergy transfer by the work, $\dot{E}_{X_i}$ is the inlet exergy transfer by the mass, $\dot{E}_{X_o}$ is the outlet exergy transfer by the mass, and $\dot{E}_{X_D}$ is the exergy destruction. It is equal to zero because the combined cycle power plant is in a steady state.

Equation 19 displays the exergy transfer by mass after ignoring kinetic and potential exergy.

$$\dot{E}_X = \dot{E}_{X_{ph}} + \dot{E}_{X_{ch}} \quad (19)$$

where $\dot{E}_{X_{ph}}$ is the physical exergy and $\dot{E}_{X_{ch}}$ is the chemical exergy.

The physical exergy can be calculated according to Equation 20 [63].

$$\dot{E}_{X_{ph}} = \dot{m}[(h - h_o) - T_o(s - s_o)] \quad (20)$$

where $\dot{m}$ is mass flowrate, h is the enthalpy, h_o is the ambient enthalpy, T_o is the ambient temperature, s is the entropy, and s_o is the ambient entropy.

The physical exergy of the ideal gases can be calculated according to the following Equation [64].

$$\dot{E}_{X_{ph}} = \dot{E}_X^T + \dot{E}_X^P \quad (21)$$

$$\dot{E}_X^T = \dot{m}\, C_P \left[(T - T_o) - T_o \ln\frac{T}{T_o}\right] \quad (22)$$

$$\dot{E}_X^P = \dot{m}\, R T_o \ln\frac{P}{P_o} \quad (23)$$

where $\dot{E}_X^T$ is the physical exergy under temperature effect, $\dot{E}_X^P$ is the physical exergy under pressure effect, T is the temperature, R is the gas constant, is the pressure, and P_o is the ambient pressure.

The chemical exergy of mixture can be calculated according to Equation 24 [65], [66].

$$\dot{E}_{X_{mix}}^{\ ch} = \dot{m}\left[\sum_{i=1}^{n} X_i \dot{E}_X^{\ ch_i} + RT_o \sum_{i=1}^{n} X_i \, Ln X_i\right] \quad (24)$$

where $\dot{E}_{X_{mix}}^{\ ch}$ is the chemical exergy of mixture, X_i is the molar fraction, and $\dot{E}_X^{\ ch_i}$ is the chemical exergy.

The combustion gas molar fraction can be measured by employing the following equations [67].

$$\lambda = \frac{0.058\, \dot{m}_a}{\dot{m}_f} \quad (25)$$

$$X_{N_2} = \frac{7.524\, \lambda}{1 + 9.6254\lambda} \quad (26)$$

$$X_{O_2} = \frac{2\,(\lambda - 1)}{1 + 9.6254\lambda} \tag{27}$$

$$X_{CO_2} = \frac{1 + 0.0028\lambda}{1 + 9.6254\lambda} \tag{28}$$

$$X_{H_2O} = \frac{2.0972}{1 + 9.6254\lambda} \tag{29}$$

where λ is the air-fuel molar ratio.

Equation 30 displays the ratio rate between the fuel exergy and fuel lower heating value [68].

$$\xi = \frac{e_{X_f}}{LHV_f} \tag{30}$$

where ξ is the exergy-lower heating value ratio of the fuel that can be calculated by employing Equations 31 and 32 for a chemical formula C_xH_y [69]. While e_{X_f} is the specific exergy of the fuel and LHV_f is the fuel lower heating value.

Regarding gaseous fuels. Usually close to 1 [70].

$$\xi = 1.033 + 0.0169\,y/x - 0.0698/x \tag{31}$$

Regarding liquid fuels.

$$\xi = 1.04224 + \ 0.011925\,y/x - 0.042/x \tag{32}$$

Equation 33 can be used to calculate the exergy efficiency of GT [71].

$$\eta_{II,GT} = \frac{\dot{W}_{net,GT}}{\dot{E}_{X_f}} \tag{33}$$

where $\eta_{II,GT}$ is the gas turbine exergy efficiency and $\dot{E}_{X_f}$ is the fuel exergy.

Equation 34 can be used to calculate the exergy efficiency of the CCPP [72].

$$\eta_{II,CCPP} = \frac{\dot{W}_{net,GT} + \dot{W}_{net,ST}}{\dot{E}_{X_f}} \tag{34}$$

where $\eta_{II,CCPP}$ is the combined cycle power plant exergy efficiency.

The fuel exergy rate and product exergy rate for each component are detailed in Table 1. All components' heat transfer to the surrounding environment was ignored except the condenser because the heat transfer from the condenser to the environment is very high compared to other components and can not be ignored.

TABLE I. THE FUEL AND PRODUCT EXERGY OF EACH COMPONENT

Component	Fuel Exergy Rate (kW)	Product Exergy Rate (kW)
Air Compressor	$\dot{W}_{AC}$	$\dot{E}x_2 - \dot{E}x_1$
Combustion Chamber	$\dot{E}x_2 + \dot{E}x_f$	$\dot{E}x_3$
Gas Turbine	$\dot{E}x_3 - \dot{E}x_4$	$\dot{W}_{GT}$
Heat Recovery Steam Generator	$\dot{E}x_4 - \dot{E}x_5$	$\dot{E}x_6 + \dot{E}x_7 - \dot{E}x_{10}$
Steam Turbine	$\dot{E}x_6 + \dot{E}x_7 - \dot{E}x_8$	$\dot{W}_{ST}$
Condenser	$\dot{E}x_8 + \dot{W}_F$	$\dot{E}x_9 + \dot{E}_{X,heat}$
Pump	$\dot{W}_{Pump}$	$\dot{E}x_{10} - \dot{E}x_9$

The exergy destruction and exergy efficiency of each component can be found in the following equations [73].

- **Air compressor**

Equation 35can be used to calculate the exergy destruction of the air compressor while Equation 36 can be used to calculate the exergy efficiency of the AC.

$$\dot{E}_{X_D} = \dot{E}x_1 + \dot{W}_{AC} - \dot{E}x_2 \tag{35}$$

$$\eta_{II} = \frac{\dot{E}x_2 - \dot{E}x_1}{\dot{W}_{AC}} \tag{36}$$

- **Combustion Chamber**

Equations 37 and 38 can be used to determine the exergy destruction and exergy efficiency of the CC, respectively.

$$\dot{E}_{X_D} = \dot{E}x_2 + \dot{E}x_f - \dot{E}x_3 \tag{37}$$

$$\eta_{II} = \frac{\dot{E}x_3}{\dot{E}x_2 + \dot{E}x_f} \tag{38}$$

- **Gas turbine**

The exergy destruction and exergy efficiency for the GT can be determined by using Equations 39 and 40, respectively.

$$\dot{E}_{X_D} = \dot{E}x_3 - \dot{E}x_4 - \dot{W}_{GT} \tag{39}$$

$$\eta_{II} = \frac{\dot{W}_{GT}}{\dot{E}x_3 - \dot{E}x_4} \tag{40}$$

- **Heat recovery steam generation**

Equations 41 and 42 can be used to determine the exergy destruction and exergy efficiency of the HRSG, respectively.

$$\dot{E}_{X_D} = \dot{E}x_4 + \dot{E}x_{10} - \dot{E}x_5 - \dot{E}x_6 - \dot{E}x_7 \tag{41}$$

$$\eta_{II} = \frac{\dot{E}x_6 + \dot{E}x_7 - \dot{E}x_{10}}{\dot{E}x_4 - \dot{E}x_5} \tag{42}$$

- **Steam Turbine**

The exergy destruction and exergy efficiency for the ST can be determined by using Equations 43 and 44, respectively.

$$\dot{E}_{X_D} = \dot{E}x_6 + \dot{E}x_7 - \dot{E}x_8 - \dot{W}_{ST} \tag{43}$$

$$\eta_{II} = \frac{\dot{W}_{ST}}{\dot{E}x_6 + \dot{E}x_7 - \dot{E}x_8} \tag{44}$$

- **Condenser**

Equations 45 and 46 can be used to determine the exergy destruction and exergy efficiency of the condenser, respectively.

$$\dot{E}_{X_D} = \dot{E}x_8 + \dot{W}_F - \dot{E}x_9 - \dot{E}_{X_{heat}} \tag{45}$$

$$\eta_{II} = \frac{\dot{E}x_9 + \dot{E}_{X_{heat}}}{\dot{E}x_8 + \dot{W}_F} \tag{46}$$

- **Pump**

Equations 47 and 48 can be used to calculate the exergy destruction and exergy efficiency of the pump, respectively.

$$\dot{E}_{X_D} = \dot{E}x_9 + \dot{W}_{Pump} - \dot{E}x_{10} \tag{47}$$

$$\eta_{II} = \frac{\dot{E}x_{10} - \dot{E}x_9}{\dot{W}_{Pump}} \tag{48}$$

2.3. Exergoeconomic Analysis

The cost-effectiveness and performance of the CCPP can be assessed by an exergoeconomic study, which integrates exergy and economic evaluations. Exergoeconomic analysis facilitates systems to reduce costs associated with exergy destruction. In order to do the exergoeconomic analysis, the specific exergy costing approach is utilized [74]. It entails determining the system's exergy rates at each state point [75]. Finding the system-wide cost equilibrium is an essential part of exergoeconomic analysis. Here is the fundamental equation utilized in exergoeconomics to determine the cost equilibrium of each system component [76], [77], [78].

$$\sum_{outlet} \dot{C}_{o,k} + \dot{C}_{work,k} = \dot{C}_{heat,k} + \sum_{inlet} \dot{C}_{i,k} + \dot{Z}_k \tag{49}$$

$$\sum \left(c_o \dot{E}_{x_o}\right)_k + c_{w,k}\dot{W}_k = c_{q,k}\dot{E}_{x_{q,k}} + \sum \left(c_i \dot{E}_{x_i}\right)_k + \dot{Z}_k \tag{50}$$

where $\dot{C}$ is the cost rate, c is the cost per exergy, and $\dot{Z}$ is the total cost of capital investment plus the cost of operation and maintenance and can be calculated by employing Equation 51.

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \tag{51}$$

where $\dot{Z}_k^{CI}$ is the capital investment cost and can be calculated according to Equation 52 while $\dot{Z}_k^{OM}$ is the operating and maintenance cost can be calculated according to Equation 53.

$$\dot{Z}_k^{CI} = \left(\frac{CRF}{\tau}\right).Z_k \tag{52}$$

$$\dot{Z}_k^{OM} = \frac{\gamma_k \times Z_k}{\tau} \tag{53}$$

where CRF is the capital recovery factor and can be calculated by employing Equation 54 [79] and Z is the purchase cost. While τ is the plant operation time in the year and γ is the maintenance factor.

$$\mathrm{CRF} = \frac{i(i+1)^n}{(i+1)^n - 1} \tag{54}$$

where i is the interest rate and n is the total number of years that the system is operational.
Equation 55 can be used to determine the cost destruction [80].

$$\dot{C}_{D,k} = c_{f,k}\dot{E}_{D,k} \tag{55}$$

$$c_{f,k} = \frac{\dot{C}_{f,k}}{\dot{E}_{f,k}} \tag{56}$$

where $\dot{C}_{D,k}$ is the cost destruction and c_f is the fuel cost per exergy. While $\dot{C}_{f,k}$ and $\dot{E}_{f,k}$ is the fuel cost rate and fuel exergy rate of the components, respectively.
Equation 57 can be used to determine the exergoeconomic factor [81].

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{57}$$

where f_k is the exergoeconomic factor.
The purchasing equipment cost can be calculated as the following formula [82], [83], [84].

- **Air compressor**

The purchase cost of the AC can be calculated by employing Equation 58.

$$Z_{AC} = 44.71 \times \dot{m}_a \times \frac{1}{0.95 - \eta_{AC}} \times \frac{P_2}{P_1} \times \ln\left(\frac{P_2}{P_1}\right) \tag{58}$$

- **Combustion chamber**

The purchase cost of the CC can be calculated according to Equation 59.

$$Z_{CC} = 28.98 \times \dot{m}_a \times \left(1 + e^{0.015(T_3 - 1540K)}\right) \tag{59}$$

- **Gas turbine**

The purchase cost of the GT can be calculated by employing Equation 60.

$$Z_{GT} = 301.45 \times \dot{m}_g \times \frac{1}{0.94 - \eta_{GT}} \times \ln\left(\frac{P_3}{P_4}\right) \times \left(1 + e^{0.025(T_3 - 1540K)}\right) \tag{60}$$

- **Heat recovery steam generator**

The purchase cost of the HRSG can be calculated according to Equations 61-67.

$$Z_{HRSG} = 4131.8 \times \sum_i f_{p,i} \times f_{T,Steam,i} \times f_{T,Gas,i} \times \left(\frac{\dot{Q}_i}{LMTD_i}\right)^{0.8} + 13380 \times \sum_j f_{p,j} \times \dot{m}_{steam,j} + 1489.7 \times (\dot{m}_{gas})^{1.2} \tag{61}$$

$$f_{p,i} = 0.0971 \times \frac{P_i}{3\ MPa} + 0.9029 \quad (62)$$

$$\mathrm{f_{T,Steam,i}} = 1 + \mathrm{e}^{\left(\frac{\mathrm{T_{out,s,i}} - 830\mathrm{K}}{500\mathrm{K}}\right)} \quad (63)$$

$$\mathrm{f_{T,Gas,i}} = 1 + \mathrm{e}^{\left(\frac{\mathrm{T_{out,g,i}} - 990\mathrm{K}}{500\mathrm{K}}\right)} \quad (64)$$

$$LMTD_{HP} = \frac{(T_4 - T_6) - \left(T_{g2}^{HP} - T_{10}\right)}{ln\left(\frac{(T_4 - T_6)}{\left(T_{g2}^{HP} - T_{10}\right)}\right)} \quad (65)$$

$$LMTD_{LP} = \frac{\left(T_{g2}^{HP} - T_7\right) - (T_5 - T_{10})}{ln\left(\frac{\left(T_{g2}^{HP} - T_7\right)}{(T_5 - T_{10})}\right)} \quad (66)$$

$$T_{g2}^{HP} = T_{g1} - \frac{\dot{m}_{s,HP} \times \left(h_{s,exit}^{HP} - h_{s,in}^{HP}\right)}{\dot{m}_g \times C_{pg}} \quad (67)$$

where $f_{p,i}$ is the Conversion factor of gas pressure, $\mathrm{f_{T,Steam,i}}$ is the conversion factor for outlet steam temperature, $\mathrm{f_{T,Gas,i}}$ is the conversion factor for outlet gas temperature, $\dot{Q}_i$ is the heat transfer rate of HRSG, and $LMTD_i$ is the logarithmic mean temperature difference.

- **Steam turbine**

The purchase cost of the ST can be calculated by employing Equation 68.

$$\mathrm{Z_{ST}} = 3880.5 \times \dot{W}_{ST}^{\ 0.7} \times \left(1 + (\frac{1 - 0.95}{1 - \eta_{ST}})^3\right) \times \left(1 + 5 \times e^{\left(\frac{T_{in} - 866K}{10.42K}\right)}\right) \quad (68)$$

- **Condenser**

The purchase cost of the condenser can be calculated by employing Equation 69 [85].

$$\mathrm{Z_{Cond}} = 1773 \times \dot{m}_8 \quad (69)$$

- **Pump**

The pump purchase cost can be calculated by employing Equation 70 [86].

$$\mathrm{Z_{Pump}} = 3540 \times \dot{W}_{Pump}^{\ 0.71} \quad (70)$$

The exergy cost balance of CCPP components is displayed in Table 2 [87].

TABLE II. THE EXERGY COST BALANCE OF EACH COMPONENT.

Component	Cost Balance	Auxiliary Equation
Air Compressor	$\dot{C}_1 + \dot{Z}_{AC} + \dot{C}_{W,AC} = \dot{C}_2$	$c_1 = 0$ $c_{W,AC} = c_{W,GT}$
Combustion Chamber	$\dot{C}_2 + \dot{C}_F + \dot{Z}_{CC} = \dot{C}_3$	$c_2 = c_3$
Gas Turbine	$\dot{C}_3 + \dot{Z}_{GT} = \dot{C}_4 + \dot{C}_{W,GT}$	$c_3 = c_4$
Heat Recovery Steam Generator	$\dot{C}_4 + \dot{C}_{10} + \dot{Z}_{HRSG} = \dot{C}_5 + \dot{C}_6 + \dot{C}_7$	$c_4 = c_5$
Steam Turbine	$\dot{C}_6 + \dot{C}_7 + \dot{Z}_{ST} = \dot{C}_8 + \dot{C}_{W,ST}$	$c_6 + c_7 = c_8$
Condenser	$\dot{C}_8 + \dot{C}_{W,F} + \dot{Z}_{Cond} = \dot{C}_9 + \dot{C}_{Heat,Cond}$	$c_8 = c_9$
Pump	$\dot{C}_9 + \dot{Z}_{Pump} + \dot{C}_{W,Pump} = \dot{C}_{10}$	–

2.4. Exergoenvironmental Analysis

The combustion reaction, which is dependent on many characteristics, including the adiabatic flame temperature, is responsible for the quantity of CO and NO_x emissions in the CC. Finding the adiabatic flame temperature in the CC is the first step in calculating the pollutant emission rate. The following equation can be used to compute the adiabatic flame temperature [88].

$$T_{PZ} = A\sigma^{\alpha} \exp(\beta(\sigma + \lambda)^2)\, \pi^{x^*} \theta^{y^*} \psi^{z^*} \quad (71)$$

where T_{PZ} is the flame temperature, σ is the standard deviation defined based on the mass or molar fuel-air ratio (ϕ), π is the dimensionless pressure (P_2/P_o), θ is the dimensionless temperature (T_2/T_o), and ψ is the atomic ratio ($\psi = 4$).

$$\sigma = \begin{cases} \phi, & \phi < 1 \\ \phi - 0.7, & \phi \geq 1 \end{cases} \tag{72}$$

In addition, the following equations establish x, y, and z as quadric functions of σ:

$$x^* = a_1 + b_1\sigma + c_1\sigma^2 \tag{73}$$

$$y^* = a_2 + b_2\sigma + c_2\sigma^2 \tag{74}$$

$$z^* = a_3 + b_3\sigma + c_3\sigma^2 \tag{75}$$

where A, α, β, λ, a, b, and c are constant parameters. The pollutant emissions ($g/kg\ of\ fuel$) are delineated as follows [89]:

$$m_{NOx} = \frac{0.15 \times 10^{16} \times \tau^{0.5} \times \exp(-71100/T_{PZ})}{P_2^{0.05} \times (\Delta P_2/P_2)^{0.5}} \tag{76}$$

$$m_{CO} = \frac{0.179 \times 10^{9} \times \exp(7800/T_{PZ})}{P_2^{2} \times \tau \times (\Delta P_2/P_2)^{0.5}} \tag{77}$$

$$m_{UHC} = \frac{0.755 \times 10^{11} \times \exp(9756/T_{PZ})}{P_2^{2.3} \times \tau^{0.1} \times (\Delta P_2/P_2)^{0.6}} \tag{78}$$

where m_{NOx} represents the nitrogen oxide emissions, m_{CO} is the carbon monoxide emissions, and m_{UHC} is the unburned hydrocarbon. While τ represents the amount of time spent in the combustion zone ($\tau = 0.002\ sec$) and $\Delta P_2/P_2$ represents the nondimensional pressure drop in the CC is equal to (0.05).
Equation 79 can be utilised to get the overall cost of CCPP [90].

$$\dot{C}_{Tot} = \dot{C}_f + \sum_k \dot{Z}_k + \dot{C}_D + \dot{C}_{env} \tag{79}$$

$$\dot{C}_{env} = C_{NOx}\dot{m}_{NOx} + C_{CO}\dot{m}_{CO} \tag{80}$$

$$\dot{C}_f = c_f \dot{m}_f \times LHV \tag{81}$$

where $\dot{C}_{env}$ is the environmental impact cost, C_{NOx} and C_{CO} are damage cost equal 6.853 $\$/kg_{NOx}$ and 0.02086 $\$/kg_{CO}$, respectively [91].

TABLE III. CONSTANTS FOR EQUATION (71,73–75) [92].

Constants	$0.3 \leq \varphi \leq 1.0$			$1.0 < \varphi \leq 1.6$	
	$0.92 \leq \theta < 2$	$2 \leq \theta \leq 3.2$		$0.92 \leq \theta < 2$	$2 \leq \theta \leq 3.2$
A	2361.7644	2315.752		916.8261	1246.1778
α	0.1157	−0.0493		0.2885	0.3819
β	−0.9489	−1.1141		0.1456	0.3479
λ	−1.0976	−1.1807		−3.2771	−2.0365
a_1	0.0143	0.0106		0.0311	0.0361
b_1	−0.0553	−0.045		−0.078	−0.085
c_1	0.0526	0.0482		0.0497	0.0517
a_2	0.3955	0.5688		0.0254	0.0097
b_2	−0.4417	−0.55		0.2602	0.502
c_2	0.141	0.1319		−0.1318	−0.2471
a_3	0.0052	0.0108		0.0042	0.017
b_3	−0.1289	−0.1291		−0.1781	−0.1894
c_3	0.0827	0.0848		0.098	0.1037

3. RESULTS AND DISCUSSION

To meet the increasing worldwide demand for energy while reducing negative impacts on the environment, CCPPs are needed. By reusing the gas turbine's waste heat to generate more electricity, these systems which incorporate both gas and steam turbine cycles are able to outperform traditional thermal power plants in terms of efficiency. The versatility and efficiency of CCPPs in satisfying energy demands while minimizing environmental effects have earned them widespread recognition. A thorough comprehension of the thermodynamic performance of these systems can be gained from energy and exergy evaluations, which emphasize the importance of reducing exergy destruction in critical components including gas turbines, HRSG, and steam turbines. In order to find inefficiencies that are costly and to guide improvements in design that are cost-effective, exergoeconomic analysis combines exergy insights with economic factors. In addition, by assessing the emissions and resource depletion linked to exergy degradation, the new discipline of exergoenvironmental analysis fills the void between thermodynamic performance and environmental considerations. Energy efficiency, cost-effectiveness, and environmental sustainability can be achieved by optimisingoptimizing the design and operation of CCPPs through the systematic combination of these approaches. This review compiles the most recent findings, approaches, and case studies, highlighting how they all work together to make current power plants more efficient and environmentally friendly. Table 4 presents the most recent research studies on this subject.

TABLE IV. RECENT SCIENTIFIC INVESTIGATIONS CONCERNING THE CCPP.

Refs	Energy Analysis	Exergy Analysis	Exergoeconomic Analysis	Exergoenvironmental Analysis	Findings and Accomplishments
[93]	×	✓	×	×	The CC was the main contributor to exergy destruction.
[94]	×	✓	×	×	The CC exergy efficiency increases when the AC ratio increases.
[95]	✓	×	×	×	The total efficiency and overall power output improve as the compression ratio rises.
[96]	✓	×	×	×	The GT performance is influenced by the fuel's LHV. A higher LHV indicates better performance.
[97]	✓	×	×	×	Temperature has a greater effect on GT performance than relative humidity. Exhaust gas energy loss and fuel usage both decrease with rising ambient temperature.
[98]	✓	✓	×	×	Regenerative systems are the optimal choice for reducing exergy losses from exhaust gases.
[99]	✓	✓	×	×	Using exhaust gas to heat the inlet fuel improved the CCPP performance.
[100]	✓	×	×	×	The GT power generation decreases by 0.5 to 0.9% for every 1°C increase in air temperature.
[101]	✓	×	×	×	Solar energy was used as a preheater for air compressors to save 64% of fuel.
[102]	✓	×	×	×	Flue gas was used in the absorption cooling system to cool inlet air and solar energy to increase the steam temperature in HRSG to increase CCPP thermal energy from 48.96% to 51.5%.
[103]	✓	×	×	×	Used cascaded waste heat recovery from GT to increase the thermal efficiency from 28.5% to 41.3%.
[104]	✓	✓	✓	×	The solar energy was used for air compressor heating that enters the CC in CCPP to improve the GT thermal efficiency from 28.4% to 76.5%.
[105]	✓	✓	×	×	Reheating makes the ideal compression ratio for compressors, which maximizes exergy efficiency. Optimal compressor compression ratios are 10 for systems without reheat, 14 for systems with one

					stage of reheat, and 20 for systems with two stages of reheat.
[106]	✓	✓	✓	×	Integrated solar collectors with CCPP increase power plant exergy efficiency by 17.34% and thermal efficiency by 17.96% with the total unit cost of production being 12.39 $/MWh.
[107]	✓	✓	×	×	The GT output power increases by 6-12% for every 10°C drop in intake air temperature.
[108]	✓	✓	×	×	Compared to exergy efficiency, thermal efficiency was higher.
[109]	✓	×	×	×	The incorporation of vapor compression cooling with a GT to cool the intake air compressor enhances the efficiency of the plant by 4.88% and increases the plant's work production by 14.77%.
[110]	✓	×	×	×	Cooling the inlet air from 23°C to 8°C increased the CCPP power output by 24.2MW.
[111]	✓	✓	✓	✓	Evaporative cooling systems entail substantially cheaper initial installation costs compared to vapor compression cooling systems. However, evaporative systems have more repair and maintenance expenses.
[112]	✓	✓	×	×	The inlet air cooling system was discovered to enhance the system and raise the GT power output by more than 7%.
[113]	✓	×	✓	×	The chiller system's yearly GT output power is 117,027 MWh, incurring an annual cost of $7,624,548.90. The yearly power augmentation from GT employing evaporative cooling is 86,118 MWh, incurring a total annual expenditure of $1,524,779.70. Evaporative cooling is a cost-effective, low-maintenance, low-electricity-consumption.
[114]	✓	✓	×	×	The reheating system significantly influences the minimization of exergy losses in steam turbines, with triple-pressure HRSG accounting for only approximately 2.58% of the total exergy loss rate.
[115]	✓	×	✓	×	The linear parabolic solar collectors were used to preheat compressed air before it was delivered into the CC. This resulted in a 22% decrease in fossil fuel usage.
[47]	✓	✓	✓	✓	Enhancing the total exergy efficiency from 56.8% to 57.3%. In addition, the CC was the primary source of exergy destruction and cost destruction.

[116]	✓	✓	×	×	The exergy destruction of the CC decreases with an increase in the GT inlet temperature.
[117]	✓	✓	✓	×	The augmentation of pressure ratio and isentropic efficiency in air compressor, along with enhanced GT efficiency, improves the thermodynamic performance of the system. The CC, HRSG, and GT exhibit the greatest total cost rate. These components are the most critical elements of exergoeconomic analysis.
[118]	✓	✓	×	×	The findings indicated that 60.9% of the overall exergy destruction transpires in the CC, which serves as the primary source of exergy destruction inside the system.
[119]	✓	✓	×	×	The CC has the highest exergy destruction rate, accounting for 77.61% of the plant's total exergy destruction rate.
[120]	×	×	✓	×	The CC was the primary source of cost destruction.
[121]	×	✓	✓	×	The CC was the primary source of exergy destruction and cost destruction.
[122]	✓	✓	×	×	The total exergy destruction in all components decreased by 2% after installing the intercooler cycle.
[123]	✓	✓	✓	✓	Regenerative CCPP is more efficient than simple CCPP. The optimum thermal efficiency of regenerative CCPP is 58.2% while for simple CCPP is 56.6%.
[124]	✓	✓	×	×	Improved the CCPP performance by integrating it with the solar collector.
[125]	✓	✓	✓	×	The heat transfer losses in the HRSG and the flue gas exhaust to the stack in a triple-pressure less than those of the double-pressure. The CCPP exergy efficiency was enhanced by 1.05% when triple-pressure reheat was employed. The triple-pressure reheat in steam generation elevates the overall costs of the plant by 6%.
[126]	✓	✓	✓	×	The net power output rose from 167.3 MW to 258.2 MW following the incorporation of the steam turbine and organic turbine with the GT.
[127]	✓	✓	✓	✓	The CC performed the highest exergy destruction and cost destruction. The GT produced exhaust emissions of 0.21 kg/s, requiring a forested area of 116,300 m2.
[128]	✓	✓	×	✓	Multi-objective optimization results demonstrate a 10.6% enhancement in the overall exergy destruction rate and an 8.3% reduction in CO_2 emissions.

[129]	×	×	✓	✓	The CC was the primary source of cost destruction . To enhance the environmental efficiency of CCPP, exergy destruction in the CC and ST must be minimized.
[130]	✓	✓	×	×	Increasing compressor pressure ratios from 6 to 16 enhances GT exergy efficiency by around 11% in the CCPP.
[131]	✓	×	×	×	By adding an absorption chiller to dual-cool the intake air and turbine coolant, the CCPP power generation was increased by 8.2%.
[132]	✓	✓	×	×	Adding a solar concentrator with an area of 2010 m2 in CCPP increased the total power output from 293.6 to 325.3 MW.
[133]	✓	✓	✓	✓	Applying the optimal values improved exergy efficiency by around 6% and decreased CO_2 emissions by about 5.63%.
[134]	✓	✓	✓	✓	With multi-objective optimization, the energy efficiency and exergy efficiency of the power plant are enhanced by 8.12% and 10%, respectively while reducing the cost rate and emissions.
[135]	✓	✓	✓	✓	Improved GT performance in two stages. Firstly, the air preheat was used with a bottom Brayton cycle to improve the GT efficiency from 30.76% to 38.83% with a total destruction cost of 58.17 $/h. In the second stage, the hot water unit, thermoelectric generator, and absorption chiller were integrated with a bottom Brayton cycle to improve the GT efficiency from 30.76% to 40.77% with a total destruction cost of 49.1 $/h. However, emissions were reduced by optimizing efficiency and minimizing waste.
[136]	✓	×	×	✓	The proposed numerical model utilizing the Broyden Fletcher Goldfarb Shanno algorithm improves efficiency by simulating diverse operating scenarios, the resulting increase in power output from 452 to 462.1 MW through the optimization of environmental factors.
[137]	✓	×	×	✓	Increasing thermal efficiency of CCPP from 47.26% to 61.1% that incorporated with air-cooling system and preheater operated by solar energy.
[138]	✓	✓	×	✓	The solid oxide fuel cell and thermoelectric generator were integrated with the steam turbine. The overall energy efficiency attained is 62.54%, and CO emissions are substantially reduced.

4. CONCLUSIONS

An integrated strategy encompassing energy, exergy, exergoeconomic, and exergoenvironmental evaluations is essential for the efficient functioning and sustainability of CCPPs. Energy analysis is a fundamental technique for assessing system performance and identifying areas with persistent energy losses and exergy analysis advances the comprehension of energy utilization by identifying methods to diminish entropy generation and enhance system efficiency. Exergoeconomic analysis is essential for quantifying the financial impact of exergy destruction and providing a cost-benefit assessment for improving plant efficiency. This method allows for improved budgeting of power plant improvements by quantifying energy losses in monetary terms. Evaluating and mitigating the environmental impacts of CCPPs, particularly concerning pollutant discharge and greenhouse gas emissions, necessitates an exergoenvironmental analysis. This approach is beneficial for formulating long-term energy strategies as it ensures that efficiency enhancements align with environmental regulations. There have been great advances in CCPP performance, but there are still obstacles to overcome, especially with regard to lowering exergy destruction and increasing economic feasibility. A number of important approaches should be thought about in order to improve the effectiveness and longevity of CCPPs. To optimize the utilization of waste heat, advanced energy recovery systems are integrated. These systems include organic Rankine cycles, phase-change materials, and high-efficiency heat recovery steam generators. Combining power generation from fossil fuels with renewable energy sources like solar thermal, biomass, or hydrogen results in a smaller carbon footprint and less fuel use. The integration of these analytical techniques provides a comprehensive strategy for improving the operational efficiency, economic feasibility, and environmental sustainability of CCPPs, leading to future energy generation that is less harmful to the environment.

Conflicts Of Interest

The author's paper explicitly states that there are no conflicts of interest to be disclosed.

Funding

The author's paper clearly indicates that the research was conducted without any funding from external sources.

Acknowledgment

The author acknowledges the institution for their commitment to fostering a research-oriented culture and providing a platform for knowledge dissemination.

References

[1] M. B. Jamnani, D. S. K. Ting, R. Carriveau, and A. Kardgar, “Energy, exergy, environmental (3E) and parametric assessment of a triple-pressure reheat combined-cycle power plant,” *J. Energy Resour. Technol. Trans. ASME*, vol. 143, no. 11, 2021, doi: 10.1115/1.4049738.
[2] T. k. Ibrahim *et al.*, “The optimum performance of the combined cycle power plant: A comprehensive review,” *Renew. Sustain. Energy Rev.*, vol. 79, no. May 2016, pp. 459–474, 2017, doi: 10.1016/j.rser.2017.05.060.
[3] S. Mohtaram, H. G. Sun, J. Lin, W. Chen, and Y. Sun, “Multi-Objective Evolutionary Optimization & 4E analysis of a bulky combined cycle power plant by CO2/ CO/ NOx reduction and cost controlling targets,” *Renew. Sustain. Energy Rev.*, vol. 128, no. July 2019, 2020, doi: 10.1016/j.rser.2020.109898.
[4] J. G. Koomey, “Worldwide electricity used in data centers,” *Environ. Res. Lett.*, vol. 3, no. 3, 2008, doi: 10.1088/1748-9326/3/3/034008.
[5] O. Mahian, M. R. Mirzaie, A. Kasaeian, and S. H. Mousavi, “Exergy analysis in combined heat and power systems: A review,” *Energy Convers. Manag.*, vol. 226, no. October, p. 113467, 2020, doi: 10.1016/j.enconman.2020.113467.
[6] N. Noorashid and N. M. Mazlan, “Computational Study of Biofuels Effect on Pressure and Temperature Changes Across Two-spool High Bypass Turbofan Engine Components at Various Engine Rotational Speeds,” *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 92, no. 2, pp. 138–156, 2022, doi: 10.37934/arfmts.92.2.138156.
[7] T. K. Ibrahim *et al.*, “A comprehensive review on the exergy analysis of combined cycle power plants,” *Renew. Sustain. Energy Rev.*, vol. 90, no. July 2016, pp. 835–850, 2018, doi: 10.1016/j.rser.2018.03.072.
[8] G. Zhu, T. T. Chow, K. F. Fong, and C. K. Lee, “Comparative study on humidified gas turbine cycles with different air saturator designs,” *Appl. Energy*, vol. 254, no. June, p. 113592, 2019, doi: 10.1016/j.apenergy.2019.113592.

[9] M. Aliyu, A. B. AlQudaihi, S. A. M. Said, and M. A. Habib, “Energy, exergy and parametric analysis of a combined cycle power plant,” *Therm. Sci. Eng. Prog.*, vol. 15, p. 100450, 2020, doi: 10.1016/j.tsep.2019.100450.

[10] M. R. M. Yazdi, M. Aliehyaei, and M. A. Rosen, “Exergy, economic and environmental analyses of gas turbine inlet air cooling with a heat pump using a novel system configuration,” *Sustain.*, vol. 7, no. 10, pp. 14259–14286, 2015, doi: 10.3390/su71014259.

[11] A. T. Watban Khalid Fahmi, K. Reza Kashyzadeh, and S. Ghorbani, “A comprehensive review on mechanical failures cause vibration in the gas turbine of combined cycle power plants,” *Eng. Fail. Anal.*, vol. 134, no. October 2021, 2022, doi: 10.1016/j.engfailanal.2022.106094.

[12] S. N. Omar Kamal, D. A. Salim, M. S. Mohd Fouzi, D. T. Hong Khai, and M. K. Yusri Yusof, “Feasibility Study of Turbine Inlet Air Cooling using Mechanical Chillers in Malaysia Climate,” *Energy Procedia*, vol. 138, pp. 558–563, 2017, doi: 10.1016/j.egypro.2017.10.159.

[13] L. W. Kit, H. Mohamed, N. Y. Luon, H. Hasini, and L. Chan, “Modelling and Simulation of Micro Gas Turbine Performance and Exhaust Gaseous,” *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 104, no. 2, pp. 184–195, 2023, doi: 10.37934/arfmts.104.2.184195.

[14] S. F. Al-Fahed, F. N. Alasfour, and H. K. Abdulrahim, “The effect of elevated inlet air temperature and relative humidity on cogeneration system,” *Int. J. Energy Res.*, vol. 33, no. 15, pp. 1384–1394, 2009.

[15] A. K. Sharma, A. Singhania, A. Kumar, R. Roy, and B. K. Mandal, “Improvement of Gas Turbine Power Plant Performance: A Review,” *Int. J. Innov. Res. Eng. Manag.*, no. 3, pp. 658–663, 2017, doi: 10.21276/ijirem.2017.4.3.4.

[16] M. Ameri, P. Ahmadi, and A. Hamidi, “Energy, exergy and exergoeconomic analysis of a steam power plant: A case study,” *Int. J. energy Res.*, vol. 33, no. 5, pp. 499–512, 2009.

[17] Y. A. Cengel, *ThermodynamicsAn Engineering Approach 5th Edition By Yunus A Cengel: ThermodynamicsAn Engineering Approach*. Digital Designs, 2011.

[18] I. A. Urzúa, J. C. Olmedo, and E. E. Sauma, “Impact of intermittent non-conventional renewable generation in the costs of the Chilean main power system,” *Renew. Sustain. Energy Rev.*, vol. 60, pp. 810–821, 2016.

[19] O. J. Khaleel, F. Basim Ismail, T. Khalil Ibrahim, and S. H. bin Abu Hassan, “Energy and exergy analysis of the steam power plants: A comprehensive review on the Classification, Development, Improvements, and configurations,” *Ain Shams Eng. J.*, vol. 13, no. 3, p. 101640, 2022, doi: 10.1016/j.asej.2021.11.009.

[20] M. H. Ahmadi, M. A. Ahmadi, S. A. Sadatsakkak, and M. Feidt, “Connectionist intelligent model estimates output power and torque of stirling engine,” *Renew. Sustain. Energy Rev.*, vol. 50, pp. 871–883, 2015.

[21] M. A. Saeed *et al.*, “Electrical power output prediction of combined cycle power plants using a recurrent neural network optimized by waterwheel plant algorithm,” *Front. Energy Res.*, vol. 11, no. September, pp. 1–14, 2023, doi: 10.3389/fenrg.2023.1234624.

[22] M. A. Rosen and C. A. Bulucea, “Using exergy to understand and improve the efficiency of electrical power technologies,” *Entropy*, vol. 11, no. 4, pp. 820–835, 2009.

[23] R. Saidur, G. BoroumandJazi, S. Mekhilef, and H. A. Mohammed, “A review on exergy analysis of biomass based fuels,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 2, pp. 1217–1222, 2012, doi: https://doi.org/10.1016/j.rser.2011.07.076.

[24] M. H. Ahmadi *et al.*, “Thermodynamic and economic analysis of performance evaluation of all the thermal power plants: A review,” *Energy Sci. Eng.*, vol. 7, no. 1, pp. 30–65, 2019, doi: 10.1002/ese3.223.

[25] C. Casarosa, F. Donatini, and A. Franco, “Thermoeconomic optimization of heat recovery steam generators operating parameters for combined plants,” *Energy*, vol. 29, no. 3, pp. 389–414, 2004.

[26] M. R. Majdi Yazdi, F. Ommi, M. A. Ehyaei, and M. A. Rosen, “Comparison of gas turbine inlet air cooling systems for several climates in Iran using energy, exergy, economic, and environmental (4E) analyses,” *Energy Convers. Manag.*, vol. 216, no. May, p. 112944, 2020, doi: 10.1016/j.enconman.2020.112944.

[27] E. Ersayin and L. Ozgener, “Performance analysis of combined cycle power plants: A case study,” *Renew. Sustain. Energy Rev.*, vol. 43, pp. 832–842, 2015, doi: 10.1016/j.rser.2014.11.082.

[28] M. Tajik Mansouri, P. Ahmadi, A. Ganjeh Kaviri, and M. N. M. Jaafar, “Exergetic and economic evaluation of the effect of HRSG configurations on the performance of combined cycle power plants,” *Energy Convers. Manag.*, vol. 58, pp. 47–58, 2012, doi: 10.1016/j.enconman.2011.12.020.

[29] L. T. Shireef and T. K. Ibrahim, “Influence of operating parameters on the performance of combined cycle based on exergy analysis,” *Case Stud. Therm. Eng.*, vol. 40, no. September, p. 102506, 2022, doi: 10.1016/j.csite.2022.102506.

[30] N. R. Kumar, K. R. Krishna, and A. V. S. R. Raju, “Performance improvement and exergy analysis of gas turbine power plant with alternative regenerator and intake air cooling,” *Energy Eng.*, vol. 104, no. 3, pp. 36–53, 2007.

[31] B. E. Outlook, “edition. London, United Kingdom2019,” *Google Sch. There is no Corresp. Rec. this Ref.*, 2019.

[32] S. R. Park, A. K. Pandey, V. V Tyagi, and S. K. Tyagi, "Energy and exergy analysis of typical renewable energy systems," *Renew. Sustain. Energy Rev.*, vol. 30, pp. 105–123, 2014.

[33] M. Fallah, S. M. S. Mahmoudi, M. Yari, and R. A. Ghiasi, "Advanced exergy analysis of the Kalina cycle applied for low temperature enhanced geothermal system," *Energy Convers. Manag.*, vol. 108, pp. 190–201, 2016.

[34] F. Meng, L. Chen, and F. Sun, "A numerical model and comparative investigation of a thermoelectric generator with multi-irreversibilities," *Energy*, vol. 36, no. 5, pp. 3513–3522, 2011, doi: https://doi.org/10.1016/j.energy.2011.03.057.

[35] R. Kumar, "A critical review on energy, exergy, exergoeconomic and economic (4-E) analysis of thermal power plants," *Eng. Sci. Technol. an Int. J.*, vol. 20, no. 1, pp. 283–292, 2017, doi: 10.1016/j.jestch.2016.08.018.

[36] P. Ahmadi and I. Dincer, "Exergoenvironmental analysis and optimization of a cogeneration plant system using Multimodal Genetic Algorithm (MGA)," *Energy*, vol. 35, no. 12, pp. 5161–5172, 2010, doi: 10.1016/j.energy.2010.07.050.

[37] O. R. Altarawneh, A. A. Alsarayreh, A. M. Al-Falahat, M. J. Al-Kheetan, and S. S. Alrwashdeh, "Energy and exergy analyses for a combined cycle power plant in Jordan," *Case Stud. Therm. Eng.*, vol. 31, no. November 2021, p. 101852, 2022, doi: 10.1016/j.csite.2022.101852.

[38] T. K. Ibrahim and M. M. Rahman, "Optimum performance improvements of the combined cycle based on an intercooler–reheated gas turbine," *J. Energy Resour. Technol.*, vol. 137, no. 6, p. 61601, 2015.

[39] M. Hoseinpour, H. Sadrnia, M. Tabasizadeh, and B. Ghobadian, "Energy and exergy analyses of a diesel engine fueled with diesel, biodiesel-diesel blend and gasoline fumigation," *Energy*, vol. 141, pp. 2408–2420, 2017, doi: 10.1016/j.energy.2017.11.131.

[40] S. A. Salah, E. F. Abbas, O. M. Ali, N. T. Alwan, S. J. Yaqoob, and R. Alayi, "Evaluation of the gas turbine unit in the Kirkuk gas power plant to analyse the energy and exergy using ChemCad simulation," *Int. J. Low-Carbon Technol.*, vol. 17, no. April, pp. 603–610, 2022, doi: 10.1093/ijlct/ctac034.

[41] H. Aras and O. Balli, "Exergoeconomic analysis of a combined heat and power system with the micro gas turbine (MGTCHP)," *Energy Explor. Exploit.*, vol. 26, no. 1, pp. 53–70, 2008, doi: 10.1260/014459808784305824.

[42] P. Ahmadi, M. A. Rosen, and I. Dincer, "Greenhouse gas emission and exergo-environmental analyses of a trigeneration energy system," *Int. J. Greenh. Gas Control*, vol. 5, no. 6, pp. 1540–1549, 2011, doi: 10.1016/j.ijggc.2011.08.011.

[43] D. L. Igbong and D. O. Fakorede, "Exergoeconomic analysis of a 100 MW unit GE Frame 9 gas turbine plant in Ughelli, Nigeria," *Int. J. Eng. Technol.*, vol. 4, no. September, pp. 463–468, 2014.

[44] S. N. Naserabad, A. Mehrpanahi, and G. Ahmadi, "Multi-objective optimization of HRSG configurations on the steam power plant repowering specifications," *Energy*, vol. 159, pp. 277–293, 2018, doi: 10.1016/j.energy.2018.06.130.

[45] T. K. Ibrahim *et al.*, "Thermal performance of gas turbine power plant based on exergy analysis," *Appl. Therm. Eng.*, vol. 115, pp. 977–985, 2017, doi: 10.1016/j.applthermaleng.2017.01.032.

[46] A. S. Abdulsitar, A. F. Saeed, and H. H. Ismaeel, "A comparative investigation of two gas turbines utilizing natural gas and diesel fuel through energy, exergy, exergoeconomic, and exergoenvironment assessments," *Fuel*, vol. 388, no. January, p. 134515, 2025, doi: 10.1016/j.fuel.2025.134515.

[47] P. Ahmadi, I. Dincer, and M. A. Rosen, "Exergy, exergoeconomic and environmental analyses and evolutionary algorithm based multi-objective optimization of combined cycle power plants," *Energy*, vol. 36, no. 10, pp. 5886–5898, 2011, doi: https://doi.org/10.1016/j.energy.2011.08.034.

[48] M. Elwardany, A. M. Nassib, and H. A. Mohamed, "Exergy analysis of a gas turbine cycle power plant: a case study of power plant in Egypt," *J. Therm. Anal. Calorim.*, vol. 149, no. 14, pp. 7433–7447, 2024.

[49] M. S. Mohammed, "Exergoeconomic analysis and optimization of combined cycle power plants with complex configuration," *Универзитет у Београду*, 2015.

[50] P. Ahmadi and I. Dincer, "Thermodynamic analysis and thermoeconomic optimization of a dual pressure combined cycle power plant with a supplementary firing unit," *Energy Convers. Manag.*, vol. 52, no. 5, pp. 2296–2308, 2011, doi: 10.1016/j.enconman.2010.12.023.

[51] M. Galal, R. Abd El-Maksoud, and N. N. Bayomi, "Exergy analysis of a steam power station in a sulfuric acid plant," *Case Stud. Therm. Eng.*, vol. 53, p. 103937, 2024.

[52] "GAZ İ ANTEP UNIVERSITY GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES EXERGETIC AND THERMOECONOMIC PERFORMANCE ANALYSIS AND OPTIMIZATION OF DIESEL ENGINE POWERED COGENERATION SYSTEMS Exergetic and Thermoeconomic Performance Analysis and Optimization of Die," no. August, 2008.

[53] T. K. Ray, R. Ganguly, and A. Gupta, "Exergy analysis for performance optimization of a steam turbine cycle," in *2007 IEEE Power Engineering Society Conference and Exposition in Africa-PowerAfrica*, IEEE, 2007, pp. 1–8.

[54] G. R. Ahmadi and D. Toghraie, "Energy and exergy analysis of Montazeri Steam Power Plant in Iran," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 454–463, 2016, doi: 10.1016/j.rser.2015.11.074.

[55] M. Ameri, P. Ahmadi, and S. Khanmohammadi, "Exergy analysis of a 420 MW combined cycle power plant," *Int. J. energy Res.*, vol. 32, no. 2, pp. 175–183, 2008.

[56] M. Ameri and N. Enadi, "Thermodynamic modeling and second law based performance analysis of a gas turbine power plant (exergy and exergoeconomic analysis)," *J. Power Technol.*, vol. 92, no. 3, pp. 183–191, 2012.

[57] A. Mousafarash and P. Ahmadi, "Exergy and exergo-economic based analysis of a gas turbine power generation system," *Prog. Sustain. Energy Technol. Vol II Creat. Sustain. Dev.*, vol. 93, no. 1, pp. 97–108, 2014, doi: 10.1007/978-3-319-07977-6_7.

[58] H. Hajabdollahi, P. Ahmadi, and I. Dincer, "An exergy-based multi-objective optimization of a heat recovery steam generator (HRSG) in a combined cycle power plant (CCPP) using evolutionary algorithm," *Int. J. Green Energy*, vol. 8, no. 1, pp. 44–64, 2011.

[59] I. Dincer and M. A. Rosen, "Energy, environment and sustainable development," *Appl. Energy*, vol. 64, no. 1–4, pp. 427–440, 1999.

[60] A. Cihan, O. Hacihafizoğlu, and K. Kahveci, "Energy-exergy analysis and modernization suggestions for a combined-cycle power plant," *Int. J. Energy Res.*, vol. 30, no. 2, pp. 115–126, 2006, doi: 10.1002/er.1133.

[61] B. Yuksel, U. Gunerhan, and A. Hepbasli, "Assessing Exergy-Based Economic and Sustainability Analyses of a Military Gas Turbine Engine Fueled with Various Fuels," *Energies*, vol. 13, no. 15, 2020, doi: 10.3390/en13153823.

[62] O. Shamet, R. Ahmed, and K. Nasreldin Abdalla, "Energy and exergy analysis of a steam power plant in Sudan," *African J. Eng. Technol.*, vol. 1, no. 1, 2021.

[63] S. S. Baakeem, J. Orfi, S. Alaqel, and H. Al-Ansary, "Impact of ambient conditions of arab Gulf countries on the performance of gas turbines using energy and exergy analysis," *Entropy*, vol. 19, no. 1, 2017, doi: 10.3390/e19010032.

[64] H. O. Egware and O. O. Ighodaro, "Evaluating the effect of ambient air temperature on the exergy sustainability of a 153MW gas turbine power plant," *Int. J. Thermofluids*, vol. 18, no. May, p. 100375, 2023, doi: 10.1016/j.ijft.2023.100375.

[65] A. Bejan, G. Tsatsaronis, and M. Moran, "Thermal Design & Optimization," 1996.

[66] S. Arpit, P. K. Das, and S. K. Dash, "Exergetic sustainability analysis of a naphtha-based combined cycle power plant (CCPP)," *Arab. J. Sci. Eng.*, vol. 48, no. 9, pp. 11741–11753, 2023.

[67] A. S. Abdulsitar, A. F. Saeed, and H. H. Ismaeel, "Performance Evaluation of a 1500 MW Combined Cycle Power Plant using Energy and Exergy Analysis," *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 128, no. 1, pp. 123–150, 2025, doi: 10.37934/arfmts.128.1.123150.

[68] M. B. Soultanzadeh, M. Haratian, M. Teymouri, and K. S. Branch, "Energy Equipment and Systems Mini two-shaft gas turbine exergy analysis with a proposal to decrease exergy destruction," *Energy Equip. Sys*, vol. 6, no. 2, pp. 131–141, 2018, [Online]. Available: http://energyequipsys.ut.ac.irwww.energyequipsys.com

[69] A. A. A. Abuelnuor, M. M. Hassan Suliman, M. A. Abuelnour, O. Younis, and E. F. Mohamed, "Exergy analysis of the boiler in phase 3 of the Khartoum North power plant," *Results Eng.*, vol. 21, no. January, p. 101919, 2024, doi: 10.1016/j.rineng.2024.101919.

[70] A. G. Kaviri, M. N. M. Jaafar, T. M. Lazim, and H. Barzegaravval, "Exergoenvironmental optimization of Heat Recovery Steam Generators in combined cycle power plant through energy and exergy analysis," *Energy Convers. Manag.*, vol. 67, pp. 27–33, 2013, doi: 10.1016/j.enconman.2012.10.017.

[71] E. Yohana, T. S. Utomo, M. I. Faried, M. F. H. Dwinanda, and M. E. Yulianto, "Exergy and Energy Analysis of Gas Turbine Generator X Combined Cycle Power Plant Using Cycle-Tempo Software," *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 104, no. 1, pp. 37–46, 2023, doi: 10.37934/arfmts.104.1.3746.

[72] N. Ćehajić, "Exergy Analysis of Thermal Power Plant for Three Different Loads," *Teh. Glas.*, vol. 17, no. 2, pp. 160–166, 2023, doi: 10.31803/tg-20211214151555.

[73] X. Liu, F. Liu, Z. Huo, and Q. Zhang, "Exergy and Exergoeconomic Analyses of a Byproduct Gas-Based Combined Cycle Power Plant with Air Blade Cooling," *ACS Omega*, vol. 7, no. 6, pp. 4908–4920, 2022, doi: 10.1021/acsomega.1c05502.

[74] A. Lazzaretto and G. Tsatsaronis, "SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems," *Energy*, vol. 31, no. 8–9, pp. 1257–1289, 2006.

[75] J. Nondy and T. K. Gogoi, "Exergoeconomic and environmental optimization of gas turbine-based CCHP systems: A comprehensive study with multi-objective optimization and decision making," *Int. J. Thermofluids*, vol. 23, no. August, p. 100821, 2024, doi: 10.1016/j.ijft.2024.100821.

[76] S. O. Oyedepo, R. O. Fagbenle, S. S. Adefila, and M. M. Alam, "Exergy costing analysis and performance

evaluation of selected gas turbine power plants," *Cogent Eng.*, vol. 2, no. 1, pp. 1–21, 2015, doi: 10.1080/23311916.2015.1101048.

[77] A. Valero *et al.*, "CGAM problem: Definition and conventional solution," *Energy*, vol. 19, no. 3, pp. 279–286, 1994, doi: 10.1016/0360-5442(94)90112-0.

[78] M. Nourpour, M. H. Khoshgoftar Manesh, A. Pirozfar, and M. Delpisheh, "Exergy, Exergoeconomic, Exergoenvironmental, Emergy-based Assessment and Advanced Exergy-based Analysis of an Integrated Solar Combined Cycle Power Plant," *Energy Environ.*, vol. 34, no. 2, pp. 379–406, 2023, doi: 10.1177/0958305X211063558.

[79] T. K. Gogoi, D. Lahon, and J. Nondy, "Energy, exergy and exergoeconomic (3E) analyses of an organic Rankine cycle integrated combined cycle power plant," *Therm. Sci. Eng. Prog.*, vol. 41, p. 101849, 2023.

[80] A. Baghernejad and A. Anvari-moghaddam, "Exergoeconomic and environmental analysis and multi-objective optimization of a new regenerative gas turbine combined cycle," *Appl. Sci.*, vol. 11, no. 23, 2021, doi: 10.3390/app112311554.

[81] T. Blumberg, M. Assar, T. Morosuk, and G. Tsatsaronis, "Comparative exergoeconomic evaluation of the latest generation of combined-cycle power plants," *Energy Convers. Manag.*, vol. 153, no. September, pp. 616–626, 2017, doi: 10.1016/j.enconman.2017.10.036.

[82] A. G. Memon, R. A. Memon, K. Harijan, and M. A. Uqaili, "Parametric based thermo-environmental and exergoeconomic analyses of a combined cycle power plant with regression analysis and optimization," *Energy Convers. Manag.*, vol. 92, pp. 19–35, 2015, doi: 10.1016/j.enconman.2014.12.033.

[83] L. S. Vieira, J. L. Donatelli, and M. E. Cruz, "Mathematical exergoeconomic optimization of a complex cogeneration plant aided by a professional process simulator," *Appl. Therm. Eng.*, vol. 26, no. 5–6, pp. 654–662, 2006, doi: 10.1016/j.applthermaleng.2005.04.026.

[84] P. Roosen, S. Uhlenbruck, and K. Lucas, "Pareto optimization of a combined cycle power system as a decision support tool for trading off investment vs. operating costs," *Int. J. Therm. Sci.*, vol. 42, no. 6, pp. 553–560, 2003, doi: 10.1016/S1290-0729(03)00021-8.

[85] M. Tavana, M. Deymi-Dashtebayaz, D. Dadpour, and B. Mohseni-Gharyehsafa, "Realistic Energy, Exergy, and Exergoeconomic (3E) Characterization of a Steam Power Plant: Multi-Criteria Optimization Case Study of Mashhad Tous Power Plant," *Water (Switzerland)*, vol. 15, no. 17, 2023, doi: 10.3390/w15173039.

[86] A. Baghernejad and M. Yaghoubi, "Exergoeconomic analysis and optimization of an Integrated Solar Combined Cycle System (ISCCS) using genetic algorithm," *Energy Convers. Manag.*, vol. 52, no. 5, pp. 2193–2203, 2011, doi: 10.1016/j.enconman.2010.12.019.

[87] W. Talal and A. Akroot, "An Exergoeconomic Evaluation of an Innovative Polygeneration System Using a Solar-Driven Rankine Cycle Integrated with the Al-Qayyara Gas Turbine Power Plant and the Absorption Refrigeration Cycle," *Machines*, vol. 12, no. 2, p. 133, 2024, doi: 10.3390/machines12020133.

[88] A. M. Khoshkar Vandani, M. Bidi, and M. H. Ahmadi, "Energy, exergy and environmental analyses of a combined cycle power plant under part-load conditions," *Mech. Ind.*, vol. 17, no. 6, 2016, doi: 10.1051/meca/2016019.

[89] E. J. C. Cavalcanti, T. J. S. Ribeiro, and M. Carvalho, "Exergoenvironmental analysis of a combined cycle power plant fueled by natural gas from an offshore platform," *Sustain. Energy Technol. Assessments*, vol. 46, no. January, p. 101245, 2021, doi: 10.1016/j.seta.2021.101245.

[90] S. O. Oyedepo, R. O. Fagbenle, S. S. Adefila, and M. M. Alam, "Thermoeconomic and thermoenvironomic modeling and analysis of selected gas turbine power plants in Nigeria," *Energy Sci. Eng.*, vol. 3, no. 5, pp. 423–442, 2015, doi: 10.1002/ese3.79.

[91] H. Sayyaadi, "Multi-objective approach in thermoenvironomic optimization of a benchmark cogeneration system," *Appl. Energy*, vol. 86, no. 6, pp. 867–879, 2009.

[92] P. Ahmadi and I. Dincer, "Thermodynamic and exergoenvironmental analyses, and multi-objective optimization of a gas turbine power plant," *Appl. Therm. Eng.*, vol. 31, no. 14–15, pp. 2529–2540, 2011, doi: 10.1016/j.applthermaleng.2011.04.018.

[93] A. A. Sammour, O. V Komarov, M. A. Qasim, and M. H. Haidar, "Exergetic Investigation of a Combined Cycle Power Plant: A Case Study," *J. Adv. Res. Appl. Sci. Eng. Technol.*, vol. 2, no. 2, pp. 232–248, 2024.

[94] Sandeep Kumar and Ashutosh Mishra, "Effect of air-fuel ratio and pressure ratio on the exergetic performance of combined cycle gas turbine plant components," *World J. Adv. Eng. Technol. Sci.*, vol. 8, no. 1, pp. 208–215, 2023, doi: 10.30574/wjaets.2023.8.1.0030.

[95] T. K. Ibrahim and M. M. Rahman, "Effect of Compression Ratio on Performance of Combined Cycle Gas Turbine," *Int. J. Energy Eng.*, vol. 2, no. 1, pp. 9–14, 2012, doi: 10.5923/j.ijee.20120201.02.

[96] M. Algool, E. M. Elmabrouk, and S. Alsadaie, "Performance Analysis of Awbari Gas Turbine Power Plant with Crude Oil," vol. 3, no. April, pp. 33–47, 2024.

[97] A. A. Sammour, O. V. Komarov, F. A. Lattieff, M. A. Qasim, and A. Y. Saleh, “Influence of Surrounding Air Temperature and Humidity upon the Performance of a Gas Turbine Power Plant,” *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 112, no. 1, pp. 22–37, 2023, doi: 10.37934/arfmts.112.1.2237.

[98] M. N. KHAN, “Energetic and exergetic investigation of regenerative gas turbine air-bottoming/steam -bottoming combined cycle,” *Mechanika*, vol. 27, no. 3, pp. 251–258, 2021, doi: 10.5755/j02.mech.25099.

[99] T. Chen *et al.*, “Energy and Exergy Analyses of a Combined Cycle Power Plant With Inlet Fuel Heating,” *Therm. Sci.*, vol. 26, no. 5 Part A, pp. 3677–3687, 2022, doi: 10.2298/TSCI210628296C.

[100] A. K. Shukla, A. Sharma, M. Sharma, and S. Mishra, “Performance improvement of simple gas turbine cycle with vapor compression inlet air cooling,” *Mater. Today Proc.*, vol. 5, no. 9, pp. 19172–19180, 2018.

[101] E. Bellos, C. Tzivanidis, and K. A. Antonopoulos, “Parametric analysis and optimization of a solar assisted gas turbine,” *Energy Convers. Manag.*, vol. 139, pp. 151–165, 2017, doi: 10.1016/j.enconman.2017.02.042.

[102] A. Darwish Ahmad, A. M. Abubaker, Y. S. H. Najjar, and Y. M. A. Manaserh, “Power boosting of a combined cycle power plant in Jordan: An integration of hybrid inlet cooling & solar systems,” *Energy Convers. Manag.*, vol. 214, no. January, p. 112894, 2020, doi: 10.1016/j.enconman.2020.112894.

[103] Y. S. H. Najjar, A. M. Abubaker, and A. F. S. El-Khalil, “Novel inlet air cooling with gas turbine engines using cascaded waste-heat recovery for green sustainable energy,” *Energy*, vol. 93, pp. 770–785, 2015, doi: 10.1016/j.energy.2015.09.033.

[104] S. M. Alizadeh *et al.*, “Investigation the integration of heliostat solar receiver to gas and combined cycles by energy, exergy, and economic point of views,” *Appl. Sci.*, vol. 10, no. 15, 2020, doi: 10.3390/APP10155307.

[105] T. A. Khan, “Energy and Exergy Analysis of Gas Turbine Cogeneration Power Plant,” *Int. J. Creat. Res. Thoughts*, vol. 9, no. 6, pp. 2320–2882, 2021, [Online]. Available: www.ijcrt.org

[106] W. Talal and A. Akroot, “Exergoeconomic Analysis of an Integrated Solar Combined Cycle in the Al-Qayara Power Plant in Iraq,” *Processes*, vol. 11, no. 3, 2023, doi: 10.3390/pr11030656.

[107] S. M. S. Mahmoudi, V. Zare, F. Ranjbar, and L. G. Farshi, “Energy and exergy analysis of simple and regenerative gas turbines inlet air cooling using absorption refrigeration,” *J. Appl. Sci.*, vol. 9, no. 13, pp. 2399–2407, 2009, doi: 10.3923/jas.2009.2399.2407.

[108] A. H. Ahmed, A. M. Ahmed, and Q. Y. Hamid, “Exergy and energy analysis of 150 MW gas turbine unit: A case study,” *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 67, no. 1, pp. 186–192, 2020.

[109] A. K. Mohapatra, “Thermodynamic assessment of impact of inlet air cooling techniques on gas turbine and combined cycle performance,” *Energy*, vol. 68, pp. 191–203, 2014.

[110] G. Şen *et al.*, “The effect of ambient temperature on electric power generation in natural gas combined cycle power plant—A case study,” *Energy Reports*, vol. 4, pp. 682–690, 2018, doi: 10.1016/j.egyr.2018.10.009.

[111] M. R. Majdi Yazdi, M. Aliehyaei, and M. A. Rosen, “Exergy, economic and environmental analyses of gas turbine inlet air cooling with a heat pump using a novel system configuration,” *Sustainability*, vol. 7, no. 10, pp. 14259–14286, 2015.

[112] V., “Performance Analysis and Components Irreversiblities of a (25 MW) Gas Turbine Power Plant Modeled with a Spray Cooler,” *Am. J. Eng. Appl. Sci.*, vol. 5, no. 1, pp. 35–41, 2012, doi: 10.3844/ajeassp.2012.35.41.

[113] A. M. Marzouk and A. S. Hanafi, “Thermo-economic analysis of inlet air cooling in gas turbine plants,” *J. Power Technol.*, vol. 93, no. 2, pp. 90–99, 2013.

[114] M. Babaei Jamnani and A. Kardgar, “Energy-exergy performance assessment with optimization guidance for the components of the 396-MW combined-cycle power plant,” *Energy Sci. Eng.*, vol. 8, no. 10, pp. 3561–3574, 2020, doi: 10.1002/ese3.764.

[115] M. Amelio, V. Ferraro, V. Marinelli, and A. Summaria, “An evaluation of the performance of an integrated solar combined cycle plant provided with air-linear parabolic collectors,” *Energy*, vol. 69, pp. 742–748, 2014, doi: 10.1016/j.energy.2014.03.068.

[116] K. I. Hamada, M. N. Mohammed, R. R. Jasim, and T. K. Ibrahim, “Energy and Exergy Analyses of a Combined Power Plant Based on Natural Gas Combustion,” *Tikrit J. Eng. Sci.*, vol. 30, no. 3, pp. 17–26, 2023, doi: 10.25130/tjes.30.3.3.

[117] M. Khaljani, R. K. Saray, and K. Bahlouli, “Comprehensive analysis of energy, exergy and exergo-economic of cogeneration of heat and power in a combined gas turbine and organic Rankine cycle,” *Energy Convers. Manag.*, vol. 97, pp. 154–165, 2015.

[118] A. Almutairi, P. Pilidis, and N. Al-Mutawa, “Energetic and exergetic analysis of combined cycle power plant: Part-1 operation and performance,” *Energies*, vol. 8, no. 12, pp. 14118–14135, 2015, doi: 10.3390/en81212418.

[119] G. Topal and T. Tanbay, “Energy and exergy analysis of the 1220 MW natural gas-fired Hamitabat combined cycle power plant,” *Int. J. Energy Stud.*, vol. 8, no. 4, pp. 781–808, 2023.

[120] G. M. Fellah, F. A. Mgherbi, and S. M. Aboghres, “Exergoeconomic Analysis for Unit Gt14 of South Tripoli Gas

Turbine Power Plant," *J. Mech. Ind. Eng.*, vol. 4, no. 4, pp. 507–516, 2010.

[121] A. Martin, N. I. Rivai, R. D. Amir, and Nasruddin, "Exergoeconomic Analysis of 21.6 MW Gas Turbine Power Plant in Riau, Indonesia," *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 84, no. 1, pp. 126–134, 2021, doi: 10.37934/arfmts.84.1.126134.

[122] B. N. Prasad, "Energy and exergy analysis of intercooled combustion-turbine based combined cycle power plant," *Energy*, vol. 59, pp. 277–284, 2013.

[123] A. G. Memon, R. A. Memon, and S. Qureshi, "Thermo-environmental and economic analyses of combined cycle power plants with regression modelling and optimization," *Appl. Therm. Eng.*, vol. 125, pp. 489–512, 2017.

[124] A. Baghernejad and M. Yaghoubi, "Exergy analysis of an integrated solar combined cycle system," *Renew. Energy*, vol. 35, no. 10, pp. 2157–2164, 2010, doi: 10.1016/j.renene.2010.02.021.

[125] M. T. Mansouri, P. Ahmadi, A. G. Kaviri, and M. N. M. Jaafar, "Exergetic and economic evaluation of the effect of HRSG configurations on the performance of combined cycle power plants," *Energy Convers. Manag.*, vol. 58, pp. 47–58, 2012.

[126] A. F. Kareem, A. Akroot, H. A. Abdul Wahhab, W. Talal, R. M. Ghazal, and A. Alfaris, "Exergo–Economic and Parametric Analysis of Waste Heat Recovery from Taji Gas Turbines Power Plant Using Rankine Cycle and Organic Rankine Cycle," *Sustain.*, vol. 15, no. 12, 2023, doi: 10.3390/su15129376.

[127] A. Martin, M. Barbarosa, and F. F. Nasution, "Energy, Exergy, Exergoeconomic, and Environmental (4E) Analysis of the Existing Gas Turbine Power Plants in BOB-PT. Bumi Siak Pusako-Pertamina," *CFD Lett.* , vol. 16, no. 9, pp. 1–13, 2024, doi: 10.37934/cfdl.16.9.113.

[128] F. A. Boyaghchi and H. Molaie, "Advanced exergy and environmental analyses and multi objective optimization of a real combined cycle power plant with supplementary firing using evolutionary algorithm," *Energy*, vol. 93, pp. 2267–2279, 2015.

[129] M. Kim, D. Kim, I. J. Esfahani, S. Lee, M. Kim, and C. Yoo, "Performance assessment and system optimization of a combined cycle power plant (CCPP) based on exergoeconomic and exergoenvironmental analyses," *Korean J. Chem. Eng.*, vol. 34, no. 1, pp. 6–19, 2017, doi: 10.1007/s11814-016-0276-2.

[130] R. Karaali, "Performance Analyses of Combined Cycle Power Plants," *Int. J. Comput. Exp. Sci. Eng.*, vol. 9, no. 2, pp. 165–169, 2023, doi: 10.22399/ijcesen.1310338.

[131] H. M. Kwon, T. S. Kim, J. L. Sohn, and D. W. Kang, *Performance improvement of gas turbine combined cycle power plant by dual cooling of the inlet air and turbine coolant using an absorption chiller*, vol. 163. Elsevier B.V., 2018. doi: 10.1016/j.energy.2018.08.191.

[132] V. S. Reddy, S. C. Kaushik, and S. K. Tyagi, "Exergetic analysis of solar concentrator aided natural gas fired combined cycle power plant," *Renew. Energy*, vol. 39, no. 1, pp. 114–125, 2012.

[133] A. Ganjehkaviri, M. N. Mohd Jaafar, P. Ahmadi, and H. Barzegaravval, "Modelling and optimization of combined cycle power plant based on exergoeconomic and environmental analyses," *Appl. Therm. Eng.*, vol. 67, no. 1–2, pp. 566–578, 2014, doi: 10.1016/j.applthermaleng.2014.03.018.

[134] M. A. Javadi, S. Hoseinzadeh, M. Khalaji, and R. Ghasemiasl, "Optimization and analysis of exergy, economic, and environmental of a combined cycle power plant," *Sadhana - Acad. Proc. Eng. Sci.*, vol. 44, no. 5, 2019, doi: 10.1007/s12046-019-1102-4.

[135] M. Zoghi, N. Hosseinzadeh, S. Gharaie, and A. Zare, "Waste heat recovery of a combined Brayton and inverse Brayton cycle for gas turbine based multi-generation hydrogen and freshwater purposes: 4E comparison with a simple coupled Brayton and inverse Brayton cycle," *Therm. Sci. Eng. Prog.*, vol. 53, no. November 2023, p. 102718, 2024, doi: 10.1016/j.tsep.2024.102718.

[136] M. S. S. Danish, Z. Nazari, and T. Senjyu, "AI-coherent data-driven forecasting model for a combined cycle power plant," *Energy Convers. Manag.*, vol. 286, 2023, doi: 10.1016/j.enconman.2023.117063.

[137] A. M. Abubaker *et al.*, "Energy and Environmental Analyses of a Solar–Gas Turbine Combined Cycle with Inlet Air Cooling," *Sustain.*, vol. 16, no. 14, 2024, doi: 10.3390/su16146229.

[138] A. A. Sinha, K. Srivastava, A. S. Rajpoot, T. Choudhary, and S. P. Pandey, "A thermodynamic approach to analyze energy, exergy, emission, and sustainability (3E-S) performance by utilizing low temperature waste heat in SOFC–CHP-TEG system," *Int. J. Hydrogen Energy*, vol. 63, pp. 1088–1104, 2024.