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Review

A critical review on energy, exergy, exergoeconomic and economic (4-E) analysis of thermal power plants

Ravinder Kumar

Department of Mechanical Engineering, Maharishi Markandeshwar University, Mullana, 133207 Haryana, India

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ABSTRACT

The growing energy supply, demand has created an interest towards the plant equipment efficiency and the optimization of existing thermal power plants. Also, a thermal power plant dependency on fossil fuel makes it a little bit difficult, because of environmental impacts has been always taken into consideration. At present, most of the power plants are going to be designed by the energetic performance criterion which is based on the first law of thermodynamics. Sometimes, the system energy balance is not sufficient for the possible finding of the system imperfections. Energy losses taking place in a system can be easily determined by using exergy analysis. Hence, it is a powerful tool for the measurement of energy quality, thereby helps to make complex thermodynamic systems more efficient. Nowadays, economic optimization of plant is also a big problem for researchers because of the complex nature. At a viewpoint of this, a comprehensive literature review over the years of energy, exergy, exergoeconomic and economic (4-E) analysis and their applications in thermal power plants stimulated by coal, gas, combined cycle and cogeneration system have been done thoroughly. This paper is addressed to those researchers who are doing their research work on 4-E analysis in various thermal power plants. If anyone extracts an idea for the development of the concept of 4-E analysis using this article, we will achieve our goal. This review also indicates the scope of future research in thermal power plants.

Contents

1. Introduction

Energy plays an important role to raise the modern economy for industry, agriculture, transport and household uses in any nation. Power plants working with fossil fuel contribute 80% of world power generation and remaining part from other resources like nuclear power, hydroelectric power, geothermal power, solar power and other energies [39]. In most of the countries country's thermal power plants are playing an important role in the energy production. So, the research work should be taken enough attention towards the optimization of these power plants. In the developing countries energy supplies are less secure because of its costlier price. Indeed, there is a need to reconsider lowest-cost energy options. Since, from an energy performance point of view, first law analysis has been found to be insufficient. So, in thermodynamic analysis of various thermal processes and plant systems, exergy analysis is getting its own importance. It is a well known fact that the total conversion of heat into work is not possible. So, that part which is available for conversion is termed as exergy. It is a property associated with the state of system and

E-mail address: rav.chauhan@yahoo.co.in

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Nomenclature

$\dot{Q}$	Net heat supplied to boiler	$\dot{m}$	Mass flow rate (kg/s)
$\dot{W}$	Net work output (MW)	$\dot{W}$	Net work output (MW)
h	Enthalpy (kJ kg^{-1})	$\dot{X}$	Exergy
s	Entropy (kJ kg^{-1} K^{-1})		

environment, now-a-days a useful tool to differentiate between internal irreversibility and energy losses in a process [127]. Thermal power plant performance can be evaluated through energetic performance criteria, which are electrical power and thermal efficiency. In recent decades, exergy analysis of plant has been found as a useful method in the design, evaluation, optimization and improvement of thermal power plants. The concept of exergy was developed by J. Willard Gibbs in 1878. It was further developed by Zoran Rant in 1957. In 1965, H. D. Baehr termed the part of energy that is converted into all other forms of energy as exergy. Exergy is based on the second law of thermodynamics and the concept of irreversible production of entropy [120,23,33,76,88]. It is the useful work potential of energy. Exergy analysis helps in finding the losses taking place in a system. By this method, energy conversion at different points, various component efficiencies and points of largest losses are easily obtainable and hence it helps in taking necessary action to decrease them [32,104]. It is found to be the best tool of the cycle optimization for given input information [103]. Exergy analysis and the area of its validity has been also carefully discussed [93,121,117]. Hence, it is a powerful way for the measurement of energy quality, thereby helps to make complex thermodynamic systems more efficient. Feng et al. [44] proposed a new method of dividing exergy losses into avoidable and inevitable exergy losses based on better understanding of process performance and improvement. Electrical power generation system development reviewed by [15] and the special attention given to the plant efficiency. Taillon and Blanchard [122] represented two novel exergy efficiency graphs in thermal power plants. Jiang et al. [59] presented a new method for modifying power plants. They analyzed the influence of the secondary air temperature and feedwater temperature on the boiler as well as on the plant using the exergy analysis theory. They predicted that with the increase of feedwater temperature the secondary air temperature also increases, thereby decreases the exergy loss in the boiler system and hence increases boiler as well as plant exergy efficiency. Recently, in a number of researchers from all over the world have focused their attention upon 4-E analysis of thermal power plant in order to optimize energy quality. Some researchers have contributed review paper on exergy analysis, which helps the young researchers to get in touch with the previous year's problems [113]. In power plants, insights have been provided into various energy and exergy efficiencies which are helpful for design engineers [63]. Improvement in thermal performance of power generation units and consuming devices can be achieved significantly by combining exergy analyses with economic analyses [129]. A new methodology was presented by [85] for a new design of power plants which helps in the thermo-economic optimization of the Plant. The main purpose of this paper is to analyze the previous work done by researchers related to thermal power plant 4-E analysis.

2. 4-E analysis of coal-fired power plant

In India, coal found to be the most important and abundant fossil fuel and about 80% of the coal produced consume by India's electricity sector. Also, this is of particular relevance as coal-fired power stations form the backbone of the Indian power generation sector. Mostly, coal-fired power plants in India operate on subcritical steam parameters with the exception of a few plants that use supercritical steam parameters. Most of the coal-fired power plants have efficiencies less than 35% by using indigenous high ash coal. Now a day, efforts are taking place to bring in highly efficient super critical technology in the country for thermal power plants. Energy analysis of coal-fired power plant is done using mass and energy balance equation as given below.

Mass balance equation:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

Energy balance equation:

$$\dot{Q} - \dot{W} = \sum \dot{m}_i (h_{out} - h_{in}) \quad (2)$$

Exergy analysis is done using equations as given in Table 1.

Mathematical models for economic and exergoeconomic analysis of coal-fired power plant can be used [77,105]. There exist a number of research papers concerning energetic and exergetic performances of coal-fired thermal power plants in the literature. For instance, thermal, metallurgical and chemical analyses of power plants can be achieved using exergy analysis [75,38]. The performance of thermal power plant can be easily defined by the help of exergy as it enables the locations, types and true magnitudes of wastes and losses [75]. Exergy analyses have been utilized as a tool for the assessment of energy quantity as well as quality in coal-fired power plant using operational data at different conditions [108,49,142,74, 80,57,36,101,109]. It was concluded that the exergy lose in the boiler can be easily reduced by providing preheating air at boiler entrance and reducing fuel to air ratio in a power plant [6,8]. The relationship between thermal power plant efficiency and the rotary air preheater total process irreversibility was proposed by Wang et al. [131]. using exergy analysis [97]. proposed operation and maintenance decisions based on exergy analysis for a 500 MWe steam turbine power plant [137]. conducted exergy analyses in a large-scale ultra-supercritical coal-fired power plant. In ammonia-water based Rankine and regenerative Rankine

Table 1
Exergy function for different energy stream conditions [35].

Description	Expression	Equations
For a pure substance	$\dot{X}. = \dot{m}\left[(h - h_o) - \dot{T}_o(s - s_o)\right]$	(3)
For a solid fuel (semi-empirical correlation)	$\dot{X} = \left[\begin{matrix}(LHV).\left(1.0438 + 0.0013.\frac{x_H}{x_C} + 0.1083.\frac{x_O}{x_C} + 0.0549.\frac{x_N}{x_C}\right) + \\ 6740.x_S\end{matrix}\right]$	(4)
For a gas phase (flue gas)	$\dot{X} = \dot{m}\left[(h - h_o) - T_o(s - s_o) + \sum \dot{x}'_k.e_k^{CH} + \overline{R}.T_o.\sum x'_k.\ln x'_k\right]$	(5)

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power generation cycle exergy analysis has been compared based on the second law of thermodynamics [73]. In an organic Rankine cycle and in micro-organic Rankine heat engines, the exergy topological method was used to present a quantitative estimation of the exergy destroyed using different working fluids [84,123,135,135], 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. [20] identified the location, magnitude and the thermodynamic inefficiencies in a solar thermal power plant using exergy analysis. The fundamentals of exergy analysis method along with minimization of entropy generation and its applicability for the system optimization were reviewed with the help of some examples [16]. Exergy analysis of raw juice production and the steam-power units of the sugar production plant successfully assesses the true thermodynamic efficiency of chemical processes [124].

In thermal power plants the optimization of the first and second reheat pressures provided using the energy efficiency and exergy balance [54]. Multi-objective optimization techniques can be used for searching the decision space frontier in a single run in supercritical coal-fired plants [133]. A system simulation calculation model has been carried out to explore the exergy destruction along with pollutant emission characteristics of the plant [133]. In a pulverized coal-fired power plant, the effects of different operating conditions and parameters on the performance of each individual component of the plant using second law analysis have been observed as well as a study based on thermoeconomics has been proposed for the cost formation of the plant [141,81]. conducted exergy and techno-economic analyses for the optimization of a double reheat system in an ultra-supercritical power plant. A systematic correlation derived for capital cost and exergy loss, also it was suggested that devices in plant approximately conform to a particular ratio value which reflects the appropriate trade-off between exergy losses and capital costs based on exergy analysis [106]. So, thermoeconomics is a promising tool for the diagnosis of complex energy systems [140]. Exergy efficiency analysis through irreversibility also helped out to reduce thermal irreversibility of the Kalina cycle using ammonia-water mixture as the working substance [89]. Also, in a high temperature Kalina cycle system, using the exergy efficiency, the performance of the cycle can be assessed [50]. Modi and Haglind [87] investigated the benefit of using Kalina cycle for a direct steam generation, central receiver solar thermal power plant with high steam temperature and pressure. Also, the thermodynamic performance of Kalina cycle was compared with a simple Rankine cycle using exergy efficiency of the plant. Singh and Kaushik [114] optimized Kalina cycle couple with a coal-fired power plant using the energy and exergy analysis.

In recent years, a number of researchers have focused their research on both the energy and exergy analysis of coal-fired power plant having different capacity [6,102,119,58,34,29,100,92,35,3,96,21,42,82,95]. In a steam power plant, energy and exergy of the boiler was analyzed [111,9]. Vandani, Bidi, and Ahmadi [128]. performed boiler blowdown heat recovery using energy and exergy analyses in steam power plants. Energy and exergy efficiencies of Rankine cycle reheat steam power plant evaluated at different operating conditions [34]. In a coal-fired supercritical thermal power plant, an energetic and exergetic analysis was performed at different load conditions [2]. Energy and exergy analysis based on the thermal efficiency, exergy efficiency, exergetic performance criterion, exergy destruction and net specific work output for irreversible single reheat Rankine cycle and the double reheat Rankine cycle was proposed by Gonca [48]. In Turkey, nine coal-fired power plant performance analyses and their comparison were performed based on energetic and exergetic methods at design conditions, which help the designer to locate and evaluate the process inefficiencies [39]. Energy and exergy analysis of the Kalina cycle system using an ammonia-water mixture was analyzed by Nasruddin et al. [91]. Gupta and Kaushik [53]. carried out an energy and exergy analysis of a proposed conceptual direct steam generation solar-thermal power plant. It was concluded that the condenser has maximum energy loss followed by solar collector field. A comparison between coal-fired and nuclear steam power plants based on energy and exergy analyses, identified areas with potential for improvement in plant performance [102].

3. 4- E analysis of gas-fired power plant

In a number of researchers concentrated their work towards an exergy analysis in gas turbine power plant. Performance characteristics of a heavy-duty gas turbine can be analyzed using exergy analysis [116]. Gas turbine combustion chamber produces largest exergy so that the compressor can decrease exergy loss due to increasing pressure ratio in the cycle [98,8,118 concluded that for combustion gas turbine based power generation system, plant efficiency is higher for full load operation than partial load operation. Also, the increase in pinch points decreases plant efficiency. (Khaldi and Adouane [69] presented an exergy analysis of a twin gas turbine power plant in Algeria. Abdul Khaliq [72] analyzed the effects of various parameters on the exergy destruction in each component, following second law analysis in trigeneration system based on the conventional gas turbine cycle. Amrollahi et al. [10] conducted an exergy analysis of a natural-gas combined-cycle power plant with a CO_2 capture unit and provided proposals for efficient energy integrated chemical absorption process. On a comparative basis, the effect of various cycle operating parameters on the thermodynamic performance of the basic-gas-turbine and intercooled-gas-turbine cycles was analyzed by Kumari [78].

Exergy and exergoeconomic analysis performed by a number of researchers in gas turbine power plant. Exergy and exergoeconomic optimization was performed by (Fouladi and Saffari [46] using genetic algorithm optimization technique. Also, exergy optimization of a gas turbine power plant was performed by Kaviri and Jaafar [67]. Chen et al. [25] presented performance analysis and optimization of an open-cycle regenerator gas-turbine power plant. Ahmadi and Dincer [5] proposed a comprehensive thermodynamic and exergoeconomic modeling of a gas turbine power plant [11] investigated the influence of reference temperature on exergy and exergoeconomic performance parameters of a natural gas fired thermal plant. (Ehyaei et al. [37] studied exergy, economic and environmental analysis to investigate the effects of inlet fogging system on the first and second law efficiencies of a typical gas turbine power plant.

Lebele-Alawa and Asuo [79] performed energy and exergy analysis of 20 MW gas turbine power plant. Thermal performance and sizing of biomass based decentralized power generation analyzed at different turbine inlet temperature, cycle pressure ratio and the heat exchanger cold end temperature difference [30]. Fagbenle et al. [43] analyzed energy and exergy of a biogas-fired integrated gasification steam injected gas turbine plant. Thermodynamic analysis of the reheat combined Brayton/Rankine power cycle achieved using second-law approach [70,139]. Parametric study of an irreversible regenerative Brayton heat engine performed with external as well as internal irreversibility [65].

4. 4- E analysis of cogeneration system

Cogeneration facilities play an important role in any country's energy strategy. Cogeneration system can be considered as one of the most sustainable energies from the viewpoints of energy conservation and environmental benefits. Researchers have paid a lot

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of attention towards the efficiency improvement of cogeneration system using exergy analysis. In the design of a cogeneration-based district energy system efficiency analysis is important [107]. In a cogeneration system, associated avoidable and unavoidable exergy destruction can be easily estimated [126,31]. Bilgen and Kaygusuz [19] calculated the chemical, physical exergy and exergy destruction of the cogeneration system by using second law analysis. It was observed that at all the steam inlet conditions in cogeneration power plants in sugar industries, increasing steam generation pressure and temperature is useful to reduce exergy losses and hence improve exergetic efficiency of the plant [62]. Saidi et al. [110]. investigated exergy method optimization for a 5 kW polymer electrolyte fuel cell with cogeneration application.

Also, a good attempt has been made by researchers in energy and exergy analysis of the cogeneration system. Kamate and Gangavati [61]. presented energy and exergy analysis of a 44-MW bagasse based cogeneration plant of a sugar mill. In the analysis, energy losses, mainly occurred in the boiler exhaust, condenser and the

Table 2
Coal-fired power plant energy, exergy and economic analysis.

References	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Findings
[139]	210, 150, 160, 150, 157, 360, 210, 165, 160.9	√	√	×	Comparison of nine power plants helps engineers and researchers for the performance improvement of both plant components and overall plant
[129]	232.6	×	√	√	By increasing the values of the thermodynamic parameters of the working fluid supplied to the turbine and by reducing the temperature differences of the net heaters, the reduction in exergy destruction can be achieved
[63]	10	√	√	×	Help engineers, researchers and policy makers to make better use of energy and exergy efficiencies in energy management for power plants.
[6]	66	√	√	×	The maximum energy loss was found in the condenser. Exergy analysis represents lost energy in condenser found to be thermodynamically insignificant due to its low quality.
[8]	250	√	√	√	The maximum energy loss occurs in the condenser and next to it boiler. The major exergy destruction has been found in the boiler. It was found that the cost of exergy destruction in boiler and turbine is higher in comparison to the other components cost.
[108]	210	×	√	×	The results predicted that the boiler causes the maximum destruction of exergy.
[49]	50	√	√	×	Maximum energy losses take place in the condenser, whereas the maximum exergy losses occur in the combustor.
[142]	600	×	√	×	The exergy loss of the boiler system found to be the most.
[80]	300	×	√	×	The results are helpful for malfunctions identification and their diagnosis in the plant. Also, it is concluded that maximum exergy destruction takes place in a boiler.
[57]	422	×	√	×	The furnace causes the maximum destruction of exergy followed by the turbine.
[36]	240	×	√	×	The boiler found to be the major source of exergy destruction of the overall plant.
[136]	600	×	√	×	The exergy efficiency of the Oxy-combustion boiler found to be higher than that of the conventional combustion boiler.
[135]	800	×	√	×	The exergy efficiency of the Oxy-combustion system is lower than that of the conventional system.
[97]	500	√	√	×	Exergy–economy driven maintenance scheduling and performance guarantee test procedures has been formulated.
[137]	660	×	√	×	Exergy destruction and losses of a large-scale ultra supercritical coal-fired power plant has been compared with existing subcritical units
[140]	300	×	√	√	This study provides the malfunction analysis and the induced malfunction evaluation
[141]	300	×	√	√	Exergy cost analysis of coal-fired power plant is analyzed using the thermoeconomic method
[134]	1100	×	√	√	A large-scale coal-fired power plant was optimized from the perspectives of thermodynamics and economics
[102]	500	√	√	×	Energy and exergy analysis of coal-fired power plant has been compared with the nuclear electrical generating station of the same capacity
[119]	660	√	√	×	Thermodynamic optimization of power plant has been done using coupled artificial neural network and genetic algorithm and found to be found to be an efficient methodology compared to the routine parametric optimization
[29]	348.5	√	√	×	Energy losses, mainly occur in the condenser while the irreversibility rate and the percentage ratio of the exergy destruction of the boiler is higher than the other components
[100]	32	√	√	×	Boiler and turbine irreversibilities yield the highest exergy losses in the power plant
[92]	300	√	√	×	Two power plants of the same capacity were compared and found that the energy loss at the condenser was the highest among major units of the power plants.
[35]	110	√	√	×	The energy loss in the condenser is thermodynamically insignificant due to its low quality and that the greatest process irreversibility and possibility for efficiency improvement is found in the boiler
[3]	200	√	√	×	Condenser found to be most wasting energy equipment while from exergy point of view boiler is the main wasting exergy equipment
[96]	500	√	√	×	Part load operation exhibits lower energy efficiency due to higher energy rejection relative to net output and poor part load exergy efficiency is due to higher exergy destruction relative to net output
[21]	150	√	√	√	Major exergy loss takes place in the boiler while condenser has a less exergy loss in comparison to other components. Costs are examined at length projected improvements shall be beneficial in increasing the efficiency in plants
[42]	7.7	√	√	×	Energy analysis has been done using energy balance and exergy analysis predicted that fluidized bed coal combustor has the largest irreversibility
[82]	300	√	√	×	Energy loss mainly takes place in condenser and in boiler exergy loss takes place at most
[95]	315	√	√	×	Mainly energy loss occurs in the condenser. In terms of exergy destruction, the major loss was found in the turbine
[2]	660	√	√	×	It was found that there is no energy loss during the combustion process but the boiler has the maximum rate of exergy destruction

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boiler found to be the major contributor to the plant's overall inefficiency. Performance evaluation of combustion gas turbine cogeneration system with reheat has been evaluated incorporating energetic and exergetic efficiency [71]. Bilgen [18]. proposed exergetic and engineering analyses as well as a simulation in gas turbine based cogeneration plants. The energy and exergy analyses of a combined cooling, heating, and power system consisting of a small-scale gas turbine, an exhaust-fired double-effect absorption chiller and a heat exchanger has been also presented [26]. In cement plant, a parameter optimization to reach the maximum exergy efficiency of the single flash steam cycle, dual-pressure steam cycle, organic Rankine cycle and the Kalina cycle used for the cogeneration has been achieved using a non-traditional optimization technique [132]. Bayrak and Gungor [14] carried out an exergy analysis of an actual diesel engine-based cogeneration plant.

5. 4-E analysis of combined-cycle power plant

In a natural gas combined cycle power plant conventional and advanced exergetic analyses was applied [94]. In gas and steam turbine combined cycles, the effects of different operating parameters on cycle performance has been presented using second law analysis [90,41]. A real combined cycle power plant exergy analysis with supplementary firing was proposed by Boyaghchi and Molaie [22]. Karrabi and Rasoulipour [64] carried out the thermal and exergy analyses of supplementary firing effects on the heat recovery steam generator at different ambient temperatures and different gas turbine loads in a 420 MW combined cycle power plant. The results predicted that the supplementary firing increases the total exergy loss, hence the total exergy efficiency of plant decreases. Hajabdollahi et al. [55] prepared a model for a heat recovery steam generator and a number of pressure levels used at combined cycle power plants using evolutionary algorithms. Al-Sulaiman et al. [7] conducted the exergy assessments of an integrated organic Rankine cycle with a biomass combustor for a trigeneration system. Haseli et al. [56] 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 double the cycle efficiency. Marrero et al. [86] optimized a combined triple power cycle using second law analysis. Analysis of a combined power and refrigeration cycle was proposed by Vidal et al. [130]. Tiwari et al. [125]. presented an exergy analysis of the combined Brayton/Rankine power cycle. The results concluded that in the gas turbine, combustion chamber has more exergy losses in comparison to other components. A comprehensive exergy analysis thermodynamic model was developed for a combined Rankine and absorption refrigeration cycle [45]. In a combined cycle gas turbine power plant, exergy and a sensitivity analysis was carried out. It was concluded that the combustion chamber having major exergy destructions [138,60]. Gogoi and Talukdar [52] presented an exergy analysis of a combined reheat regenerative steam turbine based power cycle and water-LiBr vapor absorption refrigeration system. They observed the effect of vapor absorption refrigeration system component's temperature, boiler pressure, fuel flow rate and cooling capacity on performance, component and total system irreversibility. Bhattacharya et al. [17] investigated the effects of pressure and temperature ratios of the gas turbine system and the amount of fuel burned in the supplementary firing chamber on the thermal and exergetic efficiencies of a biomass integrated gasification combined cycle. Chen et al. [24] established a combined cooling, heating and power plant model which comprises of an irreversible closed Brayton cycle and an endoreversible four-heat-reservoir absorption refrigeration cycle. Finite time thermodynamics was used for exergy efficiency optimization of the plant. In a natural gas fired combined cycle power generation unit exergy analysis performed in the plant and exergy destruction for the components [99]. Also, the exergy analysis was performed for natural-gas fired power plants with CO_2 capture [41].

In a number of researchers have concentrated their research upon combined-cycle power plants using energy, exergy and exergoeconomic analysis. Energy and exergy analysis in combined-cycle and Rankine cycle power plants concluded that the largest exergy loss occurs in the boiler due to entropy generation in device and incomplete combustion process in a furnace [66]. Cihan et al. [27] concluded that gas turbines, combustion chambers and heat recovery steam generators were the main sources of irreversibilities during energy and exergy analysis. It was also found that based on exergetic analysis rather than energetic analysis in the comparative study of natural gas fired combined cycle power plant and solar concentrator aided natural gas fired combined cycle power plant, the utilization of solar energy for feed water heating and low pressure steam generation is more effective [115]. Energy and exergy efficiencies of the each component of a combined cycle power plant and parametric analysis has been performed [30] [89]. Athari et al. carried out energy, exergy and exergoeconomic

Table 3
Gas fired power plant energy, exergy and economic analysis.

References	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Findings
[69]	146.2	√	√	×	It was found that the combustor is the most inefficient apparatus and is the major destructor of exergy
[46]	–	×	√	√	Combustion chamber found to be most exergy destructor among all components of the plant
[67]	–	×	√	×	The exergy efficiency of the combustion chamber is much lower than that of other plant components
[116]	150	×	√	×	In the gas turbine, a chemical reaction in the combustor at full-load is one of the major sources of exergy destruction.
[78]	–	√	√	×	Comparison of basic-gas-turbine and intercooled-gas-turbine cycles from a thermodynamic point of view concluded that the rational efficiency of the intercooled-gas-turbine cycle is higher than the basic-gas-turbine cycle. Overall exergy destruction in intercooled-gas-turbine cycle is lower than the basic-gas-turbine cycle
[10]	100 (kW)	√	√	×	The performance of the plant has been analyzed for three sets of operating parameters and a trade-off in the operating condition is reached.
[11]	–	×	√	√	Thermal plant performance mainly depends on reference temperature, boiler and condenser efficiency.
[10]	262.8	×	√	×	Exergy efficiency for the chemical absorption CO_2 capture unit and CO_2 compression unit has been evaluated.
[37]	123.4	√	√	√	Inlet fogging system effect on the first and second law efficiencies has been investigated and a new function is proposed for a typical power plant optimization.
[43]	53	√	√	×	Energy efficiency was evaluated and the exergy loss in the combustor found to be the largest among all components of the plant.
[79]	20	√	√	×	The boiler found to be the major source of exergy destruction of the overall plant.
[4]	435	√	√	√	A multi-objective optimization is performed to find the best design variables.

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analyses to a biomass integrated post-firing combined-cycle power plant [12]. (Baghernejad and Yaghoubi [13] analyzed energy and exergy analysis of an integrated solar combined cycle system to assess the plant performance and pinpoint the sites of primary exergy destruction. Cziesla et al. [28] described the exergoeconomic evaluation of an externally fired combined cycle power plant.

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 [42,47,68]. The optimal design of operating parameters of a combined cycle power plant with a supplementary firing system was performed using generic algorithm non-traditional optimization technique [4]. Sanjay and Prasad [112] represented a

Table 4
Combined cycle power plant energy, exergy and economic analysis.

References	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Findings
[83]	420	×	√	×	In a combined cycle power plant, it was concluded that in comparison to other gas turbine efficiency the combustion chamber has a much lower efficiency. Next to it, major exergy loss occurs in heat recovery steam generator
[70]	–	×	√	×	In the reheat combined Brayton/Rankine power cycle half of the total exergy destruction occurs in the combustion chamber
[26]	–	√	√	×	In combined cooling, heating and power system the exergy destruction in the combustor is the largest among all the components
[94]	–	×	√	×	In a combined cycle power plant the highest exergy destruction is caused by the combustion chamber using both conventional and advanced exergetic analyses
[90]	–	√	√	×	In an integrated gasification combined cycle power plant the overall efficiency of the cycle found to be maximum at an optimum pressure ratio of the gas cycle for a given temperature ratio. The maximum exergy is destroyed in the process of gasification
[41]	–	√	√	×	In a gas-turbine combined-cycle power plant in the integration of the reforming process and the combined cycle have been investigated
[22]	420	×	√	×	In a real combined cycle power plant the sensitivity of the different parts of exergy destruction has been evaluated
[56]	–	×	√	×	Integrating a conventional gas turbine plant with a solid oxide fuel cell increase the efficiency of the cycle by twofold
[86]	–	×	√	×	A combined triple power cycle was analyzed and optimized with respect to important system parameters
[130]	–	×	√	×	A new combined cycle was proposed to produce both power and cooling simultaneously with only one heat source and using ammonia–water mixture as the working fluid
[125]	–	×	√	×	In a combined Brayton/Rankine power cycle more exergy losses occurred in the gas turbine combustion chamber using exergy analysis
[45]	–	×	√	×	In a combined power and cooling cycle it was found that the absorber, the boiler and the turbine had the major contribution to the total exergy destruction of the cycle
[138]	–	×	√	×	In a combined cycle gas turbine power plant the major exergy destructions take place in the combustion chamber.
[60]	–	×	√	×	The comparison of two plants a supercritical steam plant and a gas-steam turbine combined cycle have been analyzed and found that the higher exergy loss caused by mixing in the combustor, higher exergy waste from the heat recovery steam generator, and higher exergy loss by inefficiency in the power section
[52]	–	×	√	×	In a combined reheat regenerative steam turbine based power cycle and water–LiBr vapor absorption refrigeration system irreversibility distribution among various power cycle components shows the highest irreversibility in the cooling tower
[24]	–	×	√	×	In a combined cooling, heating and power plant the effects of compressor and gas turbine efficiencies on the optimal exergy output rate and exergy efficiency performances have been discussed
[28]	–	×	√	√	The exergoeconomic evaluation of an externally fired combined cycle power plant avoidable and unavoidable exergy destructions and investment costs are calculated for each component
[13]	–	√	√	×	A comprehensive energy and exergy analysis of the integrated solar combined cycle system has been conducted using the design plant data
[99]	–	×	√	×	Exergy analysis of a natural gas fired combined cycle power generation unit has been performed to investigate the effect of various parameters on the exergetic efficiency of the plant
[64]	–	×	√	×	In combined cycle power plants the thermal and exergy analyses of heat recovery steam generator for various operating conditions in variation of loads and the variation of ambient temperature based on the performance test data at different operating conditions has been evaluated
Hajabdollahi et al. 2011	–	×	√	×	A heat recovery steam generator used at combined cycle power plants has been modeled and validated
[51]	–	×	√	√	Thermodynamic modeling and exergoeconomic analysis has been conducted in a combined cycle power plant
[1]	–	×	√	√	A review on the exergoeconomic analysis and optimization of combined heat and power production has been presented
[47]	–	×	√	√	A method to optimize the operating parameters of a heat recovery steam generator has been proposed, in order to attempt to improve the overall efficiency of combined cycle plants
[68]	–	×	√	×	Exergy analysis and the influence of heat recovery steam generator inlet gas temperature on the steam cycle efficiency has been analyzed in a combined cycle power plant
[27,4,40]	–	√	√	×	Energy and exergy analysis has been carried out for a combined cycle power plant
[115]	–	√	√	×	Comparative energy and energetic analysis for evaluation of natural gas fired combined cycle power plant and solar concentrator aided natural gas fired combined cycle power plant has been done
[12] [17]	–	√	√	√	Energy, exergy and exergoeconomic analyses are applied to a biomass integrated post-firing combined-cycle power plant
[112]	–	×	√	×	An inter-cooled combustion-turbine based combined cycle efficiency has been maximized

Table 5
Cogeneration system energy, exergy and economic analysis.

References	Capacity (MW)	Energy analysis	Exergy analysis	Economic analysis	Findings
[99]	–	√	√	×	Kalina cycle was analyzed and found that turbine inlet condition and separator temperature affects the cycle at most
[114]	–	√	√	×	A computer simulation of a Kalina cycle coupled with a coal-fired steam power plant has been used to find the optimum operating conditions for the Kalina cycle
[84] [123] [91]	–	×	√	×	In an organic Rankine cycle operating on different working fluid, the exergy topological method was used to present a quantitative estimation of the exergy destroyed
[31]	–	×	√	×	Exergy analysis of an advanced combined cogeneration plant has been done
[19]	–	×	√	×	By using second law analysis the chemical and physical exergy and exergy destruction of the cogeneration system was calculated.
[62]	–	√	√	×	Exergy analysis of a heat-matched bagasse-based cogeneration plant was employed to evaluate overall and component efficiencies and to identify and assess the thermodynamic losses
[110]	5 kW	×	√	×	Design and exergy method optimization of a 5 kW power output polymer electrolyte fuel cell with a cogeneration application has been analyzed for maximum system efficiency and minimum entropy generation, fuel cell temperature and voltage should be as high as possible in the range of application
[61]	44 MW	√	√	×	Energy and exergy analysis of a bagasse-based cogeneration plant has been analyzed to assess the thermodynamic efficiencies and losses
[70]	–	√	√	×	In combustion gas turbine cogeneration system with reheat energetic and exergetic efficiencies have been defined
[18]	–	×	√	×	Exergetic and engineering analyses of two cogeneration cycles, one consisting of a gas turbine and the other of a gas turbine and steam turbine have been analyzed
[107]	–	√	√	×	A cogeneration-based district energy system was analyzed for efficiency analysis, accounting for both energy and exergy considerations. The exergy efficiencies are generally found to be more meaningful and indicative of system behaviour than the energy efficiencies
[132]	–	×	√	×	The exergy analysis for cogeneration in cement plant was used by means of genetic algorithms to reach the maximum exergy efficiency. Compared with other systems, the Kalina cycle could achieve the best performance in cement plant
[14]	11.52	√	√	×	Exergy analysis of an actual Diesel engine-based cogeneration plant was carried out and concluded that the total exergy destruction in the engine is mostly due to the highly irreversible combustion process in the engine, heat losses from the engine and friction
[7]	–	×	√	×	Exergy assessments of an integrated organic Rankine cycle revealed that the heating-cogeneration and trigeneration cases are less sensitive to the considered temperature and pressure variations as compared with the electrical power and cooling-cogeneration cases

comparison between an inter-cooled combustion-turbine based combined cycle and a simple cycle combustion-turbine based combined cycle to deliver enhanced performance. Exergoeconomic and environmental analysis of a combined cycle power plant for the plant optimization has been analyzed [51]. Abusoglu and Kanoglu [1] also proposed a review paper on the exergoeconomic analysis and optimization of combined heat and power production.

6. Results and discussion

In this paper, a number of research papers based on 4-E analysis in thermal power plant have been reviewed. In a number of papers are there without their capacity, so these are not mentioned in Table 2–5. A lot of research papers, including exergy analysis as well as energy, economic and exergoeconomic analysis. So, these papers have been also taken into consideration. Thermal power plants have been divided into four major categories i.e. coal-fired power plant, gas-fired power plant, cogeneration system and combined-cycle power plant for 4-E analysis. It is also noted that exergoeconomic analysis term has been considered into economic analysis category as mentioned in Tables 2–5.

7. Conclusions

This review paper explains how 4-E analysis of thermal power plants was analyzed by various researchers. In coal-fired power plants a substantial amount of work has been carried out on thermodynamic analysis of Rankine cycle. The maximum energy loss occurs in the condenser and next to it boiler. The major exergy destruction has been found in the boiler. It was found that the cost of exergy destruction in the boiler and turbine is higher in comparison to the other components cost. In case of gas fired power plant, it was found that the combustor is the most inefficient apparatus and is the major destructor of exergy. In a combined cycle power plant the highest exergy destruction is caused by the combustion chamber using both conventional and advanced exergetic analyses. So far, not much focus has been made on energy and exergy analysis of supercritical, ultra supercritical and advanced supercritical cycles. It is because of the material used can't sustain very high pressures and temperatures in the plant. At this stage, it is pertinent to recall that the efficiency of the power plant can be enhanced by operating it under supercritical conditions. This magnitude of saving that can be derived by operating the power plant with increased efficiency demands through concentrated efforts of the research community in this area. It is possible only if the metallurgical scientists are significantly progressing in the development of new material that can withstand higher temperatures and pressures.

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