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Review

Exergy Analysis of Solid Fuel-Fired Heat and Power Plants: A Review

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Academic Editor: Xidong Wang
Received: 16 November 2016; Accepted: 19 January 2017; Published: 1 February 2017

Abstract: The growing demand for energy is particularly important to engineers with respect to how the energy produced by heat and power plants can be used efficiently. Formerly, performance evaluation of thermal power plants was done through energy analysis. However, the energy method does not account for irreversibilities within the system. An effective method to measure and improve efficiency of thermal power plant is exergy analysis. Exergy analysis is used to evaluate the performance of a system and its main advantage is enhancement of the energy conversion process. It helps identify the main points of exergy destruction, the quantity and causes of this destruction, as well as show which areas in the system and components have potential for improvements. The current study is a comprehensive review of exergy analyses applied in the solid fuels heat and power sector, which includes coal, biomass and a combination of these feedstocks as fuels. The methods for the evaluation of the exergy efficiency and the exergy destruction are surveyed in each part of the plant. The current review is expected to advance understanding of exergy analysis and its usefulness in the energy and power sectors: it will assist in the performance assessment, analysis, optimization and cost effectiveness of the design of heat and power plant systems in these sectors.

Keywords: exergy; heat and power; solid fuels; system efficiencies

1. Introduction

The worldwide demand for, and consumption of energy and power are expected to increase in future years due to the expansion of urbanization, the rapid rate of industrialization and the continuous improvements being made to the standard of living [1,2]. Humankind currently uses 410×10^{18} joules per annum, which is equal to the energy content of over 90,000 billion litres of oil, i.e., commercially-traded energy [3]. Nevertheless, the rate of consumption is constrained by the available resources [4,5] and a consequence of energy sources being limited is that their efficient use requires thermal processes to be optimized, with special emphasis being placed on the energy associated with exhaust gases and other forms of waste heat [6]. The energy sector needs not only to be effective in order to meet the increasing demands for heat and electricity from society, but also to utilize the resources that are available for their production by improving the efficiency of plants.

Normally, performance assessment of a system is carried out using the concept of the first law of thermodynamics, which is based on the conservation of energy [1,7]. However, using energy alone in the efficiency analysis of processes is bound to lead to misconceptions, misevaluations and poor decisions [8]: it only embraces information of the inputs and outputs of the energy in the process and excludes its quality [9]. The use of second law analysis allows the quality of the energy to be determined, and the irreversibilities quantified, as a result of the entropy that is generated and which causes inefficiency in the process [1]. Second law analysis is often based on the concept of "exergy", also known as "available energy", "availability" or "useful energy" [8]. This enables the main sources of loss to be identified and provides directions for improving performance within the system [7].

Exergy is the maximum amount of work that can be obtained from a stream of matter, heat or work as it is brought into equilibrium with the environment [10]. The reference environment of temperature, pressure and mixture of substances found in abundance in nature must be defined: it is given a zero exergy (i.e., "dead state") [11]. Exergy analysis has been widely used in the evaluation, simulation and design of thermo-chemical and thermo-mechanical systems [12]. Its application reaches beyond technical analysis, as it is also used in thermo-economic, environmental and sustainability analyses of industrial systems [13]: exergy analysis allows for the thermodynamic assessment of energy conservation because it provides the tool for making a clear distinction between the energy lost to the environment and internal irreversibilities in the process [6]. It also represents quantitatively the useful energy, i.e., the work content of the great variety of streams (comprising mass, heat, work), that enters into the system and accounts for the exergy destroyed during a process, which is proportional to the entropy generated [14]. This destruction of exergy, or irreversibility, is a yardstick by which losses in the plant are determined and compared [7].

The energy in solid fuels can be converted into useful products through biological/biochemical and thermochemical processes [15,16]. In terms of faster reaction rate and reduction in larger amount and volume of solid materials, the thermochemical processes are more efficient than the biological methods [17]. The three main thermochemical conversion methods are combustion, pyrolysis and gasification [18]. The combustion process is a commercially viable option [19] and the most widely used method for solid fuels conversion into heat and power [15,20].

In the literature, only a few papers have taken a comprehensive view of exergy analysis on the biomass-based fuels and coal-fired heat and power plant. Saidur et al. [21] reviewed the application of exergy analysis to different biomass fuels. Their investigations were based on biomass gasification rather than conversion through combustion processes. Kaushik et al. [18] examined energy and exergy analysis of coal-fired thermal power plants. Though their studies were based on thermochemical conversion of the fuel using a combustion method, they only examined the design conditions of existing plants. To the best knowledge of the authors, there is no review of exergy analysis of biomass and coal co-fired heat and power plants. Therefore, the aim of this study is to review exergy analysis in the heat and power sector, with respect to comparing performance, making assessments of, and suggesting improvements for, coal-fired, biomass-fired and co-fired coal and biomass heat and power plants.

2. Exergy Analysis

The aim of exergy analysis is to detect and evaluate the thermodynamic imperfections of a process quantitatively and indicate possible ways of improving it [22]. Thermodynamic imperfection, or irreversibility, is a function of the generation of entropy. Exergy analysis enables system designers and engineers to identify the parts with the highest entropy generation, providing them with key points on which to focus: they can then increase the efficiency of the system and, simultaneously, lower the negative impact exerted on the environment [23]. Achieving these two objectives involves making evaluations of, and optimizing, each component in the entire system using the mass, energy, entropy and exergy flow. For a steady-state process, these balances are expressed below [23,24].

The mass balance equation can be written in the rate form of Equation (1):

$$\sum_{i} \dot{m}_i = \sum_{e} \dot{m}_e \quad (1)$$

where $\dot{m}_i$ and $\dot{m}_e$ are the mass flow rates of the fluid entering and exiting the system, respectively.

The energy rate balance for a steady-state system is expressed as Equation (2):

$$\sum_{i} \dot{E}_i + \dot{Q} = \sum_{e} \dot{E}_e + \dot{W} \tag{2}$$

where the energy rate entering and exiting the system is $\dot{E}_i$ and $\dot{E}_e$, respectively, $\dot{Q}$ is the heat rate into the system and $\dot{W}$ is the work transfer rate performed by the system.

The entropy rate balance equation is given by Equation (3):

$$\sum_{i} \dot{S}_i + \sum_{j} \frac{\dot{Q}_j}{T_j} + \dot{S}_{gen} = \sum_{e} \dot{S}_e \tag{3}$$

where $\dot{S}$ is the entropy rate of a flow and $\dot{S}_{gen}$ is the entropy generation rate.

The exergy rate balance for a system is calculated using Equation (4):

$$\sum_{i} \dot{E}x_i + \sum_{j} \left[1 - \frac{T_0}{T_j}\right] \dot{Q}_j = \sum_{e} \dot{E}x_e + \dot{W} + \dot{I} \tag{4}$$

where $\dot{Q}_j$ is the heat transfer rate at temperature T_j through the boundary at position j, $\dot{I}$ is the exergy destruction rate and T_0 is the temperature of the reference environment.

Rearranging the exergy balance in Equation (4), the irreversible (or exergy destruction) rate can be expressed by Equation (5) thus:

$$\dot{I} = \sum_{i} \dot{E}x_i - \sum_{e} \dot{E}x_e + \sum_{j} \left[1 - \frac{T_0}{T_j}\right] \dot{Q}_j - \dot{W} \tag{5}$$

Assuming there are no heat losses since the insulation of each component in the system is good, the exergy associated with the heat transfer rate in the components is zero [25], and Equation (5) becomes:

$$\dot{I} = \sum_{i} \dot{E}x_i - \sum_{e} \dot{E}x_e - \dot{W} \tag{6}$$

The exergy destruction rate due to irreversibility in a system can also be given as Equation (7):

$$\dot{I} = T_0 \dot{S}_{gen} \tag{7}$$

The exergy rate associated with a flowing stream of matter contains physical, chemical, kinetic and potential exergy [26] according to Equation (8):

$$\dot{E}x = \dot{m}(ex) = \dot{m}\left(ex^{ph} + ex^{ch} + ex^{ke} + ex^{pe}\right) \tag{8}$$

where ex^{ke} and ex^{pe} are exergy due to kinetic and potential energy, respectively, ex^{ph} is the specific physical exergy and ex^{ch} is the specific chemical exergy. Assuming that the changes in velocity and elevation of the flowing stream are negligible, then ex^{ke} and ex^{pe} can be discarded in the calculation of changes in exergy. The exergy flow rate of a stream is shown in Equation (9):

$$\dot{E}x = \dot{m}(ex) = \dot{m}\left(ex^{ph} + ex^{ch}\right) \tag{9}$$

The specific physical exergy, ex^{ph} is exergy due to the differences in the temperature and pressure of a system with respect to the reference environment [27]: it can be expressed by Equation (10) thus:

$$ex^{ph} = (h - h_0) - T_o(s - s_0) \tag{10}$$

where h_0 and s_0 are the specific enthalpy and the entropy respectively at the temperature of the reference environment.

The specific chemical exergy, ex^{ch} depends on the chemical composition of a substance in its particular state, and if it is in equilibrium with the reference environment [28]. For solid fuels, the specific chemical exergy can be estimated based on the elemental compositions of the fuel [29–37].

The second law of efficiency or exergy efficiency, η_{ex}, of any system can be defined as the ratio of the exergy transfer rate associated with the output to the exergy transfer rate associated with the input of the system [3]. It is the best variable for evaluating the performance of a thermal system and its components [38], and is expressed here in Equation (11):

$$\eta_{ex} = \frac{\dot{E}x_p}{\dot{E}x_f} = 1 - \frac{\dot{I} + \dot{E}x_L}{\dot{E}x_f} \tag{11}$$

where $\dot{E}x_f$ represents the fuel exergy rate, while $\dot{E}x_p$ and $\dot{E}x_L$ represent the exergy rate of the product and the rate of exergy loss from the system. If the heat losses from the components are neglected, then the exergy loss is zero [38] and Equation (11) can be rewritten as Equation (12):

$$\eta_{ex} = 1 - \frac{\dot{I}}{\dot{m}_f ex_f} \tag{12}$$

The first law efficiency or energy efficiency of a system is defined as the ratio of energy output rate to the energy input rate to system and is calculated using Equation (13) [18].

$$\eta_e = \frac{\dot{E}_o}{\dot{E}_i} = 1 - \frac{\dot{E}_L}{\dot{E}_i} \tag{13}$$

where $\dot{E}_o$ and $\dot{E}_i$ are energy output and energy input rate respectively. $\dot{E}_L$ is the rate of energy loss.

3. Cycle Analysis of a Solid Fuel Fired Power Plant Using the Exergy Method

The performance evaluation of the whole plant is done based on the components of the system. A detailed overview of the methods used for exergy analysis of each component of the solid fuel plant is given here using a modified Rankine cycle incorporated with feedwater heaters.

Generally, solid based fuels operate under thermodynamic cycles by using a working fluid in vapour form for the generation of power known as the "vapour power cycle" or the Rankine cycle. This cycle consists of four processes: reversible adiabatic pumping, constant-pressure heat transfer in the boiler, reversible adiabatic expansion in the turbine and constant-pressure heat transfer in the condenser [39]. Modifications of the Rankine cycle for optimal performance lead to the formation of the reheat, superheat and regenerative cycles, with the addition of feed water heaters and de-aerators. A process flow diagram of an advanced, modified Rankine cycle based on a solid-fuel combined heat and power plant is shown in Figure 1 [40], and includes both the heating of feedwater and reheating of steam.

Exergy analysis is applied to each component of the plant in order to evaluate the system's performance at steady state. The parts of the plant in question are: the combustion part of the boiler, heat exchangers in the boiler (HE), high pressure turbine (HPT), intermediate pressure turbine (IPT), low pressure turbine (LPT), condenser (Cond), condensate extraction pump (CEP), open feed water heater (OFWH), feed water pump 1 (FP1), closed feed water heater (CFWH) and feed water pump 2 (FP2). A detailed analysis is obtained by considering the mass, energy, entropy and exergy flow rate in the control volume of each individual system as well as the overall plant.

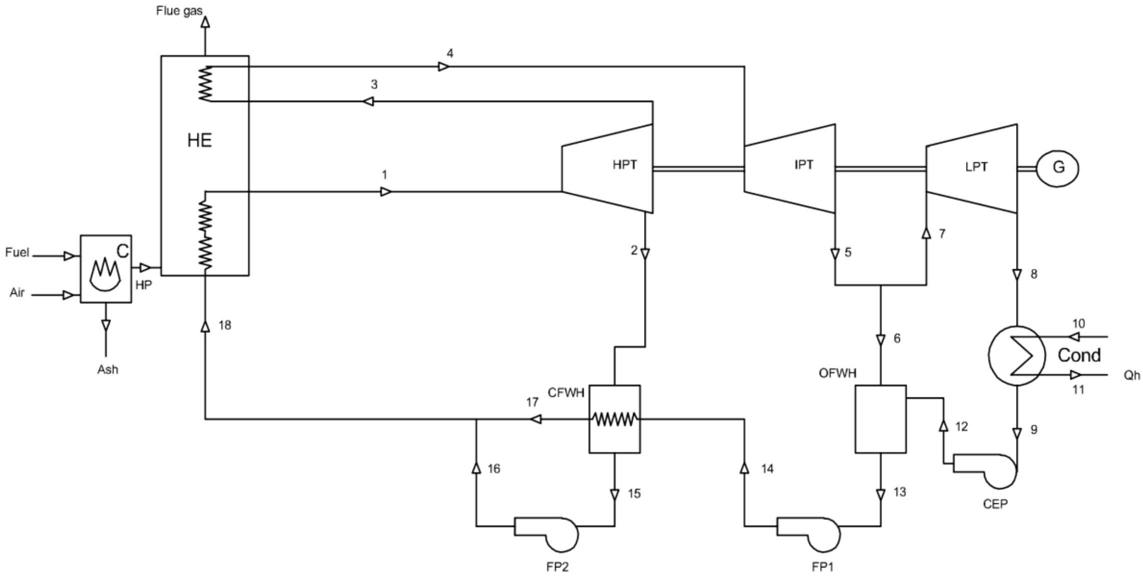

Figure 1. Flow diagram of solid fuel-fired heat and power plant model (modified from [40]).

3.1. Boiler

The boiler is divided into two parts: the combustor and the heat exchanger [12], as presented in Figure 1. If these are both assumed to be adiabatic, operating at steady state with negligible changes in their kinetic and potential energy, then each analysis in the boiler can be made by considering the mass, energy, entropy and exergy balance using the input and output conditions of the flows.

3.1.1. Boiler Combustor (C)

The exergy balance rate in the boiler combustor is given in Equation (14):

$$\dot{m}_f ex_f + \dot{m}_a ex_a = \dot{m}_{hp} ex_{hp} + \dot{m}_{ash} ex_{ash} + \dot{I}_C \quad (14)$$

The exergy destruction rate for the boiler combustor is then calculated by Equation (15) thus:

$$\dot{I}_C = \dot{m}_f (h_f - T_0 s_f) + \dot{m}_a (h_a - T_0 s_a) - \dot{m}_{hp} \left(h_{hp} - T_0 s_{hp}\right) - \dot{m}_{ash} (h_{ash} - T_0 s_{ash}) \quad (15)$$

The exergy efficiency is expressed as Equation (16):

$$\eta_{ex,C} = \frac{\dot{m}_{hp} ex_{hp}}{\dot{m}_f ex_f} \quad (16)$$

3.1.2. Boiler Heat Exchanger (HE)

The exergy balance rate for the boiler heat exchanger can be written as Equation (17):

$$\dot{m}_{hp} ex_{hp} + \dot{m}_1 ex_{18} + \left(\dot{m}_1 - \dot{m}_2\right) ex_3 = \dot{m}_{fg} ex_{fg} + \dot{m}_1 ex_1 + \left(\dot{m}_1 - \dot{m}_2\right) ex_4 + \dot{I}_{HE} \quad (17)$$

The exergy destruction rate is:

$$\begin{aligned}\dot{I}_{HE} = \dot{m}_{hp}\left(h_{hp} - T_0 s_{hp}\right) + \dot{m}_1(h_{18} - T_0 s_{18}) + \left(\dot{m}_1 - \dot{m}_2\right)(h_3 - T_0 s_3) \\ -\dot{m}_{fg}\left(h_{fg} - T_0 s_{fg}\right) - \dot{m}_1(h_1 - T_0 s_1) - \left(\dot{m}_1 - \dot{m}_1\right)(h_4 - T_0 s_4)\end{aligned} \quad (18)$$

The exergy efficiency is given as:

$$\eta_{ex,HE} = \frac{\dot{m}_1(ex_1 - ex_{18}) + (\dot{m}_1 - \dot{m}_2)(ex_4 - ex_3)}{\dot{m}_{fg}\left(ex_{hp} - ex_{fg}\right)} \quad (19)$$

The overall boiler exergy efficiency is:

$$\eta_{ex,B} = \frac{\dot{m}_1(ex_1 - ex_{18}) + (\dot{m}_1 - \dot{m}_2)(ex_4 - ex_3)}{\dot{m}_f ex_f} \quad (20)$$

3.2. High Pressure Turbine (HPT)

The exergy balance rate for the high pressure turbine is:

$$\dot{m}_1 ex_1 = \dot{m}_2 ex_2 + \left(\dot{m}_1 - \dot{m}_2\right)ex_3 + \dot{W}_{HPT} + \dot{I}_{HPT} \quad (21)$$

The exergy destruction rate in the system is expressed as:

$$\dot{I}_{HPT} = \dot{m}_1(h_1 - T_0 s_1) - \dot{m}_2(h_2 - T_0 s_2) - \left(\dot{m}_1 - \dot{m}_2\right)(h_3 - T_0 s_3) - \dot{W}_{HPT} \quad (22)$$

The exergy efficiency is written as follows:

$$\eta_{ex,HPT} = \frac{\dot{W}_{HPT}}{\dot{m}_1(ex_1 - ex_2) - \left(\dot{m}_1 - \dot{m}_2\right)ex_3} \quad (23)$$

3.3. Intermediate Pressure Turbine (IPT)

The exergy balance rate is:

$$\left(\dot{m}_1 - \dot{m}_2\right)ex_4 = \left(\dot{m}_1 - \dot{m}_2\right)ex_5 + \dot{W}_{IPT} + \dot{I}_{IPT} \quad (24)$$

The exergy destruction rate is:

$$\dot{I}_{IPT} = \left(\dot{m}_1 - \dot{m}_2\right)(h_4 - T_0 s_4) - \left(\dot{m}_1 - \dot{m}_2\right)(h_5 - T_0 s_5) - \dot{W}_{IPT} \quad (25)$$

The exergy efficiency is:

$$\eta_{ex,IPT} = \frac{\dot{W}_{IPT}}{\left(\dot{m}_1 - \dot{m}_2\right)(ex_4 - ex_5)} \quad (26)$$

3.4. Low Pressure Turbine (LPT)

The exergy balance rate is:

$$\left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)ex_7 = \left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)ex_8 + \dot{W}_{LPT} + \dot{I}_{LPT} \quad (27)$$

The exergy destruction rate is:

$$\dot{I}_{LPT} = \left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)(h_7 - T_0 s_7) - \left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)(h_8 - T_0 s_8) - \dot{W}_{LPT} \quad (28)$$

The exergy efficiency is:

$$\eta_{ex} = \frac{\dot{W}_{LPT}}{\left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)(ex_7 - ex_8)} \quad (29)$$

3.5. Condenser

The exergy balance rate is:

$$\left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)ex_8 + \dot{m}_{10}ex_{10} = \left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)ex_9 + \dot{m}_{11}ex_{11} + \dot{I}_{Cond} \quad (30)$$

The exergy destruction rate is:

$$\dot{I}_{Cond} = \left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)((h_8 - T_0 s_8) - (h_9 - T_0 s_9)) + \dot{m}_{10}((h_{10} - T_0 s_{10}) - (h_{11} - T_0 s_{11})) \quad (31)$$

The exergy efficiency is:

$$\eta_{ex,Cond} = \frac{\dot{m}_{10}(ex_{11} - ex_{10})}{\left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)(ex_8 - ex_9)} \quad (32)$$

3.6. Condensate Extraction Pump (CEP)

The exergy balance rate is:

$$\left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)ex_9 = \left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)ex_{12} - \dot{W}_{CEP} + \dot{I}_{CEP} \quad (33)$$

The exergy destruction rate is:

$$\dot{I}_{CEP} = \left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)(h_9 - T_0 s_9) - \left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)(h_{12} - T_0 s_{12}) + \dot{W}_{CEP} \quad (34)$$

The exergy efficiency is:

$$\eta_{ex,CEP} = \frac{\left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)(ex_{12} - ex_9)}{\dot{W}_{CEP}} \quad (35)$$

3.7. Open Feed Water Heater (OFWH)

The exergy balance rate is:

$$\left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)ex_{12} + \dot{m}_6 ex_6 = \left(\dot{m}_1 - \dot{m}_2\right)ex_{13} + \dot{I}_{OFWH} \quad (36)$$

The exergy destruction rate is:

$$\dot{I}_{OFWH} = \left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)(h_{12} - T_0 s_{12}) + \dot{m}_6(h_6 - T_0 s_6) - \left(\dot{m}_1 - \dot{m}_2\right)(h_{13} - T_0 s_{13}) \quad (37)$$

The exergy efficiency is:

$$\eta_{ex,OFWH} = \frac{\left(\dot{m}_1 - \dot{m}_2\right)ex_{13}}{\left(\dot{m}_1 - \dot{m}_2 - \dot{m}_6\right)ex_{12} + \dot{m}_6 ex_6} \tag{38}$$

3.8. Feed Pump (FP1)

The exergy balance rate is:

$$\left(\dot{m}_1 - \dot{m}_2\right)ex_{13} = \left(\dot{m}_1 - \dot{m}_2\right)ex_{14} - \dot{W}_{FP1} + \dot{I}_{FP1} \tag{39}$$

The exergy destruction rate is:

$$\dot{I}_{FPI} = \left(\dot{m}_1 - \dot{m}_2\right)(h_{13} - T_0 s_{13}) - \left(\dot{m}_1 - \dot{m}_2\right)(h_{14} - T_0 s_{14}) + \dot{W}_{FP1} \tag{40}$$

The exergy efficiency is:

$$\eta_{ex,FB1} = \frac{\left(\dot{m}_1 - \dot{m}_2\right)(ex_{14} - ex_{13})}{\dot{W}_{FP1}} \tag{41}$$

3.9. Closed Feed Water Heater (CFWH)

The exergy balance rate is:

$$\dot{m}_2 ex_2 + \left(\dot{m}_1 - \dot{m}_2\right)ex_{14} = \dot{m}_2 ex_{15} + \left(\dot{m}_1 - \dot{m}_2\right)ex_{17} + \dot{I}_{CFWH} \tag{42}$$

The exergy destruction rate is:

$$\dot{I}_{CFWH} = \dot{m}_2((h_2 - T_0 s_2) - (h_{15} - T_0 s_{15})) + \left(\dot{m}_1 - \dot{m}_2\right)((h_{14} - T_0 s_{14}) - (h_{17} - T_0 s_{17})) \tag{43}$$

The exergy efficiency is:

$$\eta_{ex,CFWH} = \frac{\left(\dot{m}_1 - \dot{m}_2\right)(ex_{17} - ex_{14})}{\dot{m}_2(ex_2 - ex_{15})} \tag{44}$$

3.10. Feed Pump (FP2)

The exergy balance rate is:

$$\dot{m}_2 ex_{15} = \dot{m}_2 ex_{16} - \dot{W}_{FP2} + \dot{I}_{FP2} \tag{45}$$

The exergy destruction rate is:

$$\dot{I}_{FP2} = \dot{m}_2(h_{15} - T_0 s_{15}) - \dot{m}_2(h_{16} - T_0 s_{16}) + \dot{W}_{FP2} \tag{46}$$

The exergy efficiency is:

$$\eta_{ex,FP2} = \frac{\dot{m}_2(ex_{16} - ex_{15})}{\dot{W}_{FP2}} \tag{47}$$

For a combined heat and power plant, the overall exergy efficiency can be written as [41–43]:

$$\eta_{ex,Pl} = \frac{\left(\dot{w}_{HPT} + \dot{w}_{IPT} + \dot{w}_{LPT} - \dot{w}_{CEP} - \dot{w}_{FP1} - \dot{w}_{FP2}\right) + \dot{E}x_{\dot{Q}_h}}{\dot{E}x_f} \quad (48)$$

where $\dot{E}x_{Q_h}$ is the exergy flow rate associated to the heat produced, Q_h. Here, only the useful products have been included in comparison to the exergy input. The exergy of ash and flue gas are discarded as they do not represent a product flow.

4. Application of Exergy Analysis in Solid Fuel-Fired Heat and Power Plants

The use of exergy analysis on energy conversion processes has increased in the past years and has incorporated studies of different types of heat and power plant systems for improving the efficiency of existing power plants together with developing systems and systems under design for maximizing utilization of the energy produced. In this study, we have reviewed the application of exergy analysis as an evaluator of performance in coal-fired, biomass-fired and coal-biomass co-combustion-fired power plants.

4.1. Coal-Fired Heat and Power Plants

Coal supplies about 45% of the global electricity demand [44]. It is likely to continue as a key component of the fuel mix in the generation of power even though these plants account for over 28% of the total global emissions of carbon dioxide [45]. In order to maximize the utility of coal used in the production of energy, considerable efforts need to be made to enhance the capacity and efficiency of plants whilst simultaneously reducing their environmental impact and costs of power generation [46]. Improving both the efficiency and cost effectiveness of power plants can be achieved by reducing the thermodynamic inefficiencies associated with the system that result in a reduction of the CO_2 emission per MW of electricity generated [47].

Exergy analysis has been proven to be a better way of measuring the efficiency of coal and reducing its environmental footprint by considering the effect of irreversibility in the process. A number of studies have been reported on the performance assessment and efficiency improvement of coal-based power plants using exergy analysis. Table 1 shows a summary of recent studies along with the most important conclusions that can be drawn from the application of exergy analysis when evaluating coal-fired heat and power plants.

These results identify the boiler as being the component of the plant with the highest exergy destruction as a result of the entropy generated due to irreversible combustion reactions. Exergy destruction in the combustor section of the boiler has been attributed to the chemical reaction between the fuel and air, while the large temperature difference between the combustion gases and the feedwater causes exergy destruction in the heat transfer section. The loss in the boiler in this particular case is over 50% of the total exergy destruction. As a result of the irreversibilities identified using exergy analysis, the exergetic efficiency is lower than the energetic efficiency, as can be seen in Table 1. The exergy efficiency of the power plants studied ranges from 17% to 38%. The results of the exergy destruction, heat loss and entropy generation in each component of a coal thermal power plant are summarized in Table 2 [23]. The energy analysis shows that highest energy loss occurs in the condenser, whereas the actual exergy destruction is in the boiler according to exergy analysis. The results also show that exergy destruction increases with increase in enropy generation. Hence, exergy analysis acounts for the entropy generated within the system, therefore, total exergy destruction is more than the heat loss.

Table 1. Previous studies of exergy analysis applied to coal-fired heat and power plants.

Plant Capacity (MW)	Combustion Technology	Plant Output Generation	Country	Exergy (%)	Energy Efficiency (%)	Aims	Major Results	Ref.
32	Conventional	Electricity	India	25.38	30.12	To conduct a thermodynamics analysis, using the design data of a coal–fired power plant under construction, to identify potential areas for making improvements to performance. To investigate the effects of varying the operating parameters on performance.	The largest losses occurred in the condenser when energy analysis was used. When exergy analysis was applied, however, the actual major losses were found in the boiler, which has the highest exergy destruction. This is due to heat being transferred to the working fluid, the combustion reaction and losses caused by emissions of flue gases. Increasing the steam pressure and temperature, and reducing the pressure in the steam condenser, increased the energy and exergy efficiencies of the plant.	[23]
500	Conventional	Electricity	Canada	36	37	To examine sensitivity to reasonable variations in dead-state properties of several energy and exergy values. To examine the results of energy and exergy analyses of a complex device.	The energy and exergy values were not significantly sensitive to reasonable variations in dead-state properties; the main results of energy and exergy analyses were not, generally speaking, significantly sensitive to variations in these properties. Variations in the reference temperature considered, T_0, did not affect the overall results of the energy and exergy efficiencies of the plant significantly.	[26]
50	Conventional	Electricity	India	26.95	27	To conduct an exergy analysis on the power generation of Unit V, Thermal Power Station 1 of Neyveli Lignite Corp. Ltd. (Tamil Nadu, India) in order to discover the exergy losses in various components of the plant.	The maximum energy loss (39%) occurred in the condenser while the total plant exergy destruction was calculated as being 73%. The maximum exergy loss (57.35%) occurred in the boiler, with 42.73% losses being located in the combustion.	[27]

Table 1. *Cont.*

Plant Capacity (MW)	Combustion Technology	Plant Output Generation	Country	Exergy (%)	Energy Efficiency (%)	Aims	Major Results	Ref.
1.5	Fluidized bed	Cogeneration	Turkey	20	-	To perform an exergy analysis of a cogeneration power plant, located in Çankırı, that generates electricity and steam used for producing salt.	The highest exergy destruction rate took place in the boiler, which had 85.89% of the total exergy loss in the system. Improvements to the design parameters (e.g., pressure, fluidized velocity, particle size and geometry) as well as feeding the coal from different points into the boiler should affect the combustion and overall plant efficiencies positively.	[48]
150	Conventional	Electricity	Turkey	35.19	37.88	To determine the effect of the ambient temperature on the irreversible losses and efficiency in the Catalgzi Power Plant in Zonguldak.	The irreversibility rates of the boiler were larger than for other components and increased slightly, together with total irreversibility rate, as the ambient temperature was increased from 278 to 308 K, while that of the condenser decreased with increasing ambient temperature. The boiler was the major source of exergy consumption (a result of the chemical reaction between fuel and air) and therefore has the largest potential for improvement.	[49]
7.7	Fluidized bed	Cogeneration	Turkey	23	70	To analyse the thermodynamics of a coal-fired fluidized bed power plant to show the effects that excess air, steam pressure and type of coal have on the first and second laws of efficiency in the thermal power plant.	Second law analysis revealed that the FBCC had the largest irreversibility, about 80.4% of the system's total exergy loss. The chemical reaction (72%), heat transfer processes (20%) and physical transport (8%) are the sources of irreversibilities in the combustion process in FBCC. The system's exergy efficiency increased with steam pressure, while types of coal did not affect the second law efficiency. As the excess air value increased, the exergy and energy efficiencies decreased, due to heat losses being higher when the flow rates of the flue gas increased and combustion temperature decreased: these affect the reaction rate of the fuel negatively.	[50]

Table 1. *Cont.*

Plant Capacity (MW)	Combustion Technology	Plant Output Generation	Country	Exergy (%)	Energy Efficiency (%)	Aims	Major Results	Ref.
-	Conventional	Electricity	-	34	36	To investigate the effects of feed water heaters on the performance of a coal-fired power plant using thermodynamic analysis.	For a single feed water heater, efficiency was maximized at a bled steam temperature ratio of 0.4. The efficiency of the cycle was high when the reheater pressure was 20%–25% of the boiler pressure. The exergetic loss in the boiler decreased with the addition of feed water heaters.	[51]
210	Conventional	Electricity	India	34.50	36.20	To apply exergy analysis to a coal-based thermal power plant at different operating loads, condenser pressures, with/without certain feed water heaters, and for different governor settings of the turbine valves, i.e., constant pressure operation or sliding pressure operation.	Reducing the plant load and increasing the throttle of control valves increased the irreversibilities in the cycle, whilst increasing the condenser's back pressure decreased the exergy efficiency. Withdrawal at the high pressure heaters showed a decrease in the exergy efficiency of the entire plant. The exergy efficiency of a part load operation improved when the main stream pressure prior to the turbine valves was kept in sliding mode.	[52]
500	Conventional	Electricity	India	31.47	34.33	To analyse a pulverized coal-fired power plant in a steady-state condition using energy and exergy analyses.	With the plant operating at a capacity of 460 MW, there was a reduction of approx. 8.69% and 9.10%, respectively, in the energy and exergy efficiencies compared to the ratings for the load range designed.	[53]
500	Conventional	Electricity	Canada	36	37	To compare coal and nuclear electric generating stations thermodynamically, using energy and exergy analysis.	In the coal-fired plant, 67% and 33% of the exergy consumed was due to combustion and heat transfer respectively, In the nuclear power plant, 5%, 0.9%, 0.1% and 94% of the exergy destroyed was due to the boiler, moderator cooler, heavy-water pump and reactor, respectively.	[54]

Table 1. *Cont.*

Plant Capacity (MW)	Combustion Technology	Plant Output Generation	Country	Exergy (%)	Energy Efficiency (%)	Aims	Major Results	Ref.
3 × 210	Conventional	Electricity	Turkey	31.95	37.01	To make a comparative analysis of the performance of nine coal thermal power plants from energetic and exergetic aspects.	The plant with a capacity of 320 MW had the highest exergetic performance: the exergy efficiency of a boiler with a circulating bed combustor had the highest value of all plant boilers. Boilers are vital components because they have the highest exergy losses in a plant: they should therefore be investigated so that the overall exergetic performance may be enhanced.	[55]
4 × 150	Conventional	Electricity	Turkey	31.50	38.03			
2 × 150	Conventional	Electricity	Turkey	35.19	37.88			
3 × 157	Conventional	Electricity	Turkey	28.55	37.19			
4 × 360	Conventional	Electricity	Turkey	32.46	42.64			
210	Conventional	Electricity	Turkey	35.49	37.63			
6 × 165	Conventional	Electricity	Turkey	32.35	36.08			
5 × 160.9	Conventional	Electricity	Turkey	33.09	38.44			
2 × 160	Circulating fluidized bed	Electricity	Turkey	37.88	42.12			
3 × 210	Conventional	Electricity	Turkey	31.95	37.01	To determine the most convenient point of extraction of energy for use in district heating/cooling in the conventional coal-fired Yatagan Thermal Power Plant, using thermodynamic analysis to examine the energetic and exergetic performances.	The most convenient point for extracting steam in the plant analysed was found to be the low-pressure turbine inlet stage.	[41]
500	Conventional	Electricity	Canada	36	37	To examine the effect of increasing the reheat pressure on the irreversibility rate and exergy efficiency in a coal-fired steam power plant.	The irreversibility rate associated with heat transfer in the steam generator decreased as the reheat pressure increased. However, the overall-plant exergy efficiency decreased due to the large decrease in the power output of the shaft. The decrease in the plant's thermal and exergy efficiencies over the range of reheat pressures considered was nearly 9.3%.	[56]

Table 1. *Cont.*

Plant Capacity (MW)	Combustion Technology	Plant Output Generation	Country	Exergy (%)	Energy Efficiency (%)	Aims	Major Results	Ref.
32.5	Conventional	Electricity	India	17.8	-	To analyse the performance of a coal-fired stoker power plant using exergy analysis. To investigate the effects of varying the operating temperatures of the boiler as well as the reference temperature state.	The boiler had the highest exergy destruction rate, with 77% of the total exergy loss being due to flue gas emissions, flue gas temperature, combustion reactions and heat transfer to the steam. The efficiency of the power plant increased from 18% to 42% when the temperature of the exiting steam increased from 723 K to 793 K. Varying the reference state temperature had no significant impact on the plant's overall performance.	[57]
250	Conventional	Electricity	Bangladesh	30.78	-	To investigate a coal-based thermal plant operating at sub-critical steam conditions using thermodynamic performance criteria.	The maximum exergy losses occurred in the boiler: the large exergy loss was mainly due to the combustion reaction and the high temperature difference between the combustion gas and the steam.	[58]
63	Circulating fluidized bed	Electricity	India	29.29	31.15	To establish the energy and exergy flows of each component in the coal-based circulating fluidized bed boiler in the Tuticorin Power Plant in order to identify the major area of exergy loss.	74% of the total exergy loss occurred in the furnace of the boiler system; 54.1% of the loss was located in the furnace's combustion chamber.	[59]
4 × 400	Conventional	Electricity	Saudi Arabia	35.77	-	To evaluate the design and performance of the existing Ghazlan Power Plant using the exergy concept.	The major energy losses were due to heat rejection in the condenser and stack gases, while the highest exergy losses of 70.6% of the total loss occurred in the boiler.	[60]

Table 1. *Cont.*

Plant Capacity (MW)	Combustion Technology	Plant Output Generation	Country	Exergy (%)	Energy Efficiency (%)	Aims	Major Results	Ref.
7.7	Fluidized bed	Cogeneration	Turkey	23	70	To apply conventional and advanced exergy analysis to a fluidized bed coal combustion (FBCC) and heat recovery steam generator (HRSG) in a textile plant.	A total exergy destruction of 5104 kW occurred in the system, the major part of which (4285 kW) was in the FBCC. The conventional exergy efficiencies in the FBCC and HRSG were 44.2% and 46.2%, respectively, and 53.1% and 48.1%, respectively, for advanced exergy efficiencies.	[61]
145 200 300	Conventional	Cogeneration	China	29.1 32.2 27.3	58.2 46.2 73	To investigate the most important operating parameters affecting the energetic and exergetic efficiencies, and their influence on the performance of three different coal-fired combined power (CHP) plants under various operational conditions in the district heating (DH) system.	The extraction flow rate and extraction pressure were the most important parameters of the energetic and exergetic efficiencies, respectively, in the three power plants. When the extraction ratio increased, the energetic efficiency increased, whereas the exergetic efficiency decreased. A high extraction ratio and a low extraction pressure gave the best performance in the CHP. A higher extraction pressure led to a higher heat delivery.	[42]
280	Conventional	Electricity	Australia	-	-	To conduct an exergy analysis of a coal-fired power plant in central Queensland.	The highest exergy destruction occurred in the boiler, which had 81% of the total exergy destruction in the plant. This differs to the energy balance, which showed that most of the energy loss occurred in the condenser, where 69% of the total was lost. The exergy loss in the boiler was a result of (i) its internal loss, (ii) the loss in its blowdown stream and (iii) the heat loss caused by the stream of flue gas: the greatest exergy loss occurred in the boiler´s internal heat transfer arrangement. A steam boiler has a great potential for improving the overall efficiency of a plant.	[62]

Table 2. Results from the analysis of a coal-fired thermal plant [23].

Components	Exergy Destruction (kW)	Heat Loss (kW)	Entropy Generation (kW/K)
Boiler	73,046	12,663	3312.0
Turbine	6403	3242	17.2
ACC (air cooled condenser)	1622	33	3.3
Deaerator	886	71	1.4
LP heater	552	336	2.4
HP heater	759	65	2.7
Boiler feed pump	375	140	0.0
Generator	550	656	0.9
Total	84,193	50,456	3339.9

Whilst the reference temperature does not have a noticeable effect on the energy efficiency [23], it does affect the exergy efficiency slightly, as shown in Table 3. This indicates that the surroundings of the system affect its performance when exergy analysis is used. Even though variations in the reference temperature, T_0, do not affect the overall exergy results significantly, it is important in determining the optimal operation condition in a given plant design [26]. An increase in the ambient temperature has a greater effect on the condenser compared to other components, as indicated in Table 4 [49].

Table 3. Variation in energy and exergy efficiencies at different reference temperatures [23].

Temperature (K)	Exergy Efficiency (%)	Energy Efficiency (%)
273	25.3970	30.12
283	25.3920	30.12
293	25.3884	30.12
303	25.3850	30.12
313	25.3806	30.12
323	25.3760	30.12

Table 4. The exergy rate of fuel and irreversibility rates of a power plant, kW, at different reference temperatures [49].

Reference Temperature	278 K	283 K	288 K	293 K	298 K	303 K	308 K
Fuel exergy rate	473,500	473,500	473,500	473,500	473,500	473,500	473,500
Irreversibility rate of boiler	262,520	262,561	268,602	271,643	274,684	277,725	280,766
Irreversibility rate of turbine	35,594	35,941	36,288	36,636	36,983	37,330	37,678
Irreversibility rate of condenser	9330	7982	6871	4607	2186	960	373
Irreversibility rate of feed water heaters	5256	5314	5371	5428	5486	5543	5601
Irreversibility rate of pumps	1014	1028	1042	1056	1070	1084	1098
Irreversibility rate of pipe	1418	1393	1367	1342	1317	1291	1266
Total Irreversibility rate	315,132	317,218	319,542	320,711	321,725	323,934	326,780

Taniguchi et al. [63] conducted exergy analyses of coal combustion processes with air temperatures entering the combustion chamber higher than the ambient temperature. They found that an increase in the temperature of the combustion air increases exergy efficiency. The decrease in the amount of excess air reduces flue gas losses and improves the combustion temperature [48]. Feedwater heaters can be installed to decrease the temperature difference between the flue gases and the working fluid [51]; both of these measures decrease the irreversibilities in the boiler. Operation of a power plant at full load has been shown to increase the combustion efficiency of the system and the exergy efficiency of the plant [52,53], indicating that power plants operating at their rated capacity are more economical than when operating at part loads [23]. The performance of the boiler system and the exergy efficiency increase with an increase in the steam pressure and temperature and number of feed water heaters, but a decrease in pressure in the condenser and reheater [23,51,52], while utilization of the rejected heat from the condensers as employed in the cogeneration systems improves the overall efficiency of the system [54].

The adoption of fluidized bed combustion firing technologies has been suggested as a means of improving the performance of energy conversion systems since (i) their heating surfaces located in the combustion chamber have high heat transfer rates and (ii) their combustion efficiency is superior to conventional firing systems [55]. Moreover, a fluidized bed boiler has the capacity of burning fuel mixtures with widely differing characteristics. Its low combustion temperature minimizes NO_x, and the usage of adsorbent in the bed permits the capture of sulphur [64].

4.2. Heat and Power Plants Fired by Biomass-Based Fuels

Biomass energy is derived from plant and animal material, such as wood and wood waste, agricultural crops and their waste by-products, solid municipal refuse, animal offal, waste from food processing units, aquatic plants and algae [65]. The resource known as biomass can be considered as being renewable material in which the energy of sunlight is stored in the form of chemical bonds; when the bonds between adjacent carbon, hydrogen and oxygen molecules are broken by digestion, combustion or decomposition, these substances can release their stored chemical energy [66].

The reduction in the use of coal fuels, and the need to find alternatives to fossil fuels in order to decrease CO_2 emissions, have attracted more interest in using biomass fuels as the energy carrier since biomass is perceived as being a carbon-neutral source [67,68]: biomass is thus regarded a suitable source of energy [69]. However, the overall efficiencies of biomass-fired power plants are relatively low [19,70]. Only a few papers in the literature have discussed exergy analysis applied to biomass-based heat and power plants—these are summarized in Table 5.

Li et al. [67] used conventional exergy analysis to find the sources of irreversibilities and to identify exergy destruction in the various different components of the biomass boiler. They also used advanced exergy analysis to provide comprehensive information about the avoidable exergy destruction for each component, as well as for the whole system. Their results showed that a combustion chamber with a higher degree of heat absorption has a higher exergy in the specified boiler components and that, in a biomass boiler system, the combustion process is where most of the exergy destruction that is avoidable can be found.

Kamate and Gangavati [71] applied exergy analysis to two types of steam turbines to examine the effective utilization of cogeneration power plants in the sugar industry. They found that the efficiency of the plant using a non-condensing steam turbine (back pressure steam turbine) with energy and exergy efficiencies of 0.863 and 0.307 respectively, was higher than that of a plant using an extraction (condensing) steam turbine with energy and exergy efficiencies of 0.682 and 0.260 respectively, because the former does not reject heat in the condensation process. However, when a greater amount of electricity is needed, the latter is preferred.

The generation of entropy occurs mainly in the combustion process, which prompted Baloyi et al. [72] to examine the change in its rate as a function of the air to fuel (AF) ratio in an adiabatic combustor, using wood as the source of fuel. They showed that the entropy generation rate reaches a minimum at an AF of 4.9 and equivalence ratio of 1.64.

The performances of biomass multi-generation and cogeneration power plants have also been evaluated. Soltani et al. [28] investigated a biomass multi-generation energy system that produces electricity, steam, hot water, district heating and timber heating: significant increases in both the energy and exergy efficiencies were observed in the biomass multi-generation systems compared to conventional systems. A fuel energy savings ratio of 8.2% was reported by Kamate and Gangavati [43] for a biomass cogeneration plant over the generation of heat and power in two separate plants.

Table 5. Previous studies of exergy analysis applied to biomass-fired heat and power plants.

Plant Capacity (MW)	Combustion Technology	Plant Output Generation	Country	Exergy Efficiency (%)	Energy Efficiency (%)	Aims	Major Results	Ref.
-	Conventional	Multi-generation	-	25	60	To model and evaluate a (sawdust) biomass-fired multi-generation energy system using energy and exergy analysis.	The biomass combustor was the location of the main exergy destruction in the system due to irreversible chemical reactions (combustion) and heat transfer across temperature differences between the input and output streams in the heat exchanger. The biomass input rate has a significant effect on the heat available for district heating and electricity generation: whilst it increased the exergy efficiency of the overall multi-generation system, it decreased the energy efficiency slightly.	[28]
-	Conventional	-	-	-	-	To establish a theoretical framework for the exergy analysis and advanced exergy analysis of a biomass boiler.	The combustion process dominated the exergy destruction in the main components of a biomass boiler in conventional and advanced exergy analysis. The increase in biomass moisture reduced the adiabatic flame temperature, decreased the total boiler exergy efficiency and decreased the air-fuel ratio.	[67]
4.5	Conventional	Electricity	India	16.89	18.25	To conduct an exergy analysis of a biomass-based steam plant in Karempudi.	The boiler had the highest exergy destruction, 49.17% of the total amount, due to irreversibility associated with chemical reactions.	[19]
-	Conventional	Cogeneration	India	*30.7 **26.0 *BPST **ECST	*86.3 **68.2 *BPST **ECST	To evaluate, and make an overall assessment of, a bagasse-based cogeneration plant in the sugar industry using back pressure and an extraction condensing stream turbine with a capacity of 2500 tonnes of sugar cane per day.	The back-pressure steam turbine (BPST) was the most effective configuration from an overall perspective but the extraction condensing steam plant (ECST) can produce more power. The boiler was the least efficient component and was the site of the major part of the exergy destruction, but increasing both the steam inlet pressure and temperature decreased irreversibility in the plant's components.	[71]
-	Fluidized bed	-	-	-	-	To analyse the irreversibilities generated during the combustion of wood in an adiabatic combustor.	The rate of entropy generation was entirely due to the combustion process; the irreversibilities generated reached a minimum at an air-fuel mass ratio of 4.9 in an adiabatic combustor.	[72]

Table 5. *Cont.*

Plant Capacity (MW)	Combustion Technology	Plant Output Generation	Country	Exergy Efficiency (%)	Energy Efficiency (%)	Aims	Major Results	Ref.
44	Conventional	Cogeneration	India	25	65	To evaluate bagasse-based cogeneration of power based on a sugar factory in Belgaum with a capacity of 10,000 tons of sugar cane per day (TCD) using energy and exergy analysis.	The major exergy destruction was found in the boiler, where 71% of the fuel exergy input was destroyed. Energy losses occurred mainly in the boiler exhaust and condenser, where 35 MW and 27 MW were lost to the environment, respectively. The plant's fuel energy savings ratio for the co-generation plant is 8.2% over separate generation.	[43]
-	Conventional	Cogeneration	Norway	17.3	40.6	To calculate the second law efficiency of a municipal solid waste combined heat and power plant located in Bergen using different methods to determine the chemical exergy of the fuel.	The different methods used show comparable results. The second law efficiency was 17.3% for the local surrounding temperature, the energy utilization was 40.6% and the R1 efficiency was 0.568. Focusing on the production of electricity from waste can give larger increases in exergy recovery and exergy efficiency than increasing the delivery of district or process heat.	[73]
-	-	-	-	-	-	To analyse critically, and calculate correctly, the efficiency of energy recovered from waste incineration in the new waste framework directive. To compare the energy recovery efficiency to the more scientifically-based approach of exergy efficiency.	The average energy recovery efficiencies calculated for CHP plants, plants producing mainly electricity and plants only producing heat were 0.71,0.49 and 0.64, respectively, whilst the average exergy efficiencies for these plants were 20.9%,19.4% and 18.8%, respectively. The average energy recovery efficiency of WTE plants is higher in northern Europe than in southern, as a result of the cogeneration technology that is mostly used there. The energy recovery efficiency in a WTE plant does not take into account the effect of the plant's size and the influence of climate conditions. The exergy efficiency is a reliable measure of the calculation of efficiency of energy recovery from waste incineration.	[74]

Different methods have been applied to calculate the efficiency of the incineration of municipal solid waste. Solheimslid et al. [73] used the chemical exergy of solid biomass by employing correlations, the chemical exergy obtained from the combustion equation and the absolute entropy to determine the exergy efficiency of municipal waste in a combined heat and power plant, and found both results to be in good agreement. Grosso et al. [74] examined the energy recovery efficiency, reported in the Waste Frame Directive (Directive 2008/98/EC), which accounts for the production of both power and heat. According to the directive, the energy recovery efficiency must be equal to, or exceed, 0.60 for waste incineration plants to be classified as energy recovery, rather than waste disposal, units. They analysed and compared the energy recovery efficiency to the exergy efficiency in the form of energy recovery criteria for different types of waste incineration plants in Europe, and found out that only the exergy efficiency can be considered a reliable measure.

4.3. Biomass and Coal Co-Fired Heat and Power Plant

Co-firing biomass in coal-fired boilers is regarded as being the most cost-effective approach for utilising biomass to generate power [75] because it requires little initial investment: the combustion technologies used in biomass co-firing plants are similar to those used in existing coal-fired plants [76]. Three different methods are used in biomass co-firing technology: direct, indirect and parallel co-firing. In the first method, biomass is fed directly into a boiler furnace with coal whilst the second entails a combination of gasification and combustion: the biomass is gasified and the product gas is fed into a boiler furnace containing the coal. The third method involves the biomass being burnt in a separate boiler to generate steam, which is then used in a power plant together with coal [77]. Selecting the appropriate co-firing option depends on the type of biomass available and site-specific factors, such as the types of coal handling equipment used and the arrangement of the coal firing systems installed [78,79].

Biomass co-fired with coal in traditional coal-fired boilers presents one combination of utilising fossil and renewable energy that derives the greatest benefit from both types of fuel; it leads to an effective reduction in CO_2 and SO_x emissions, and often NO_x emissions too. It represents an attractive alternative for reducing emissions of greenhouse gas from coal-fired boilers [80]. Coal-biomass co-firing prevents the concentration of chlorine, which can otherwise result in the formation of harmful alkaline and chlorine compounds on the heat transfer surfaces in boilers [81]. Progress has been made over the past years in developing the co-ultilization of biomass fuels in coal-fired boiler plants [82]. Exergy analysis can nevertheless be used to evaluate performance in order to identify both the magnitude and the locations of imperfections in the process, with the aim of improving the efficiency of the plant. Reports pertaining to exergy analyses of biomass co-combustion processes are very few and far between: Table 6 shows a summary of previous work performed in this field.

Biomass co-combustion is considered as a measure for reducing CO_2 emissions. However, the exergy losses due to irreversibility from biomass co-firing are larger than for coal-based power plants. This irrervisibility has led to decreases in the exergy efficiencies of both the boiler and the overall co-combustion plant [83]: the gas exiting the furnace has a lower temperature due to a reduction in the exergy input to the plant. Applying biomass co-firing to a fluidized bed shows that the velocity of the fluidized bed does not influence the exergy efficiency [84].

The Soma coal thermal power plant in Turkey was modified to operate as both a direct and parallel co-firing biomass plant; performance evaluation shows that biomass parallel combustion performs better, from both technical and environmental aspects, than direct co-firing which suffers from problems of corrosion and fouling in the boiler [25]. As a result of the direct contact that occurs between biomass and coal in the direct co-firing method, the alkali metals and chlorine from the biomass reduced the melting temperature of the ash: the result was slagging at the furnace walls of the boiler and a possible decrease in the efficiency of the plant [85].

Table 6. Previous studies of exergy analysis applied to coal-biomass co-combustion heat and power plants

Plant Capacity (MW)	Combustion Technology	Plant Output Generation	Country	Exergy Efficiency (%)	Energy Efficiency (%)	Aims	Major Results	Ref.
165	Conventional	Electricity	Turkey	29.04	35.91	To investigate the technical and environmental feasibility of direct and parallel co-firing of biomass * with Soma Lignite Corp. Ltd. in the Soma Thermal Power Plant, using exergy analysis. * corn cobs, cotton gin and olive pits.	Both the direct and parallel co-firing of biomass decreased the consumption rate of lignite and reduced the plant's emissions of CO_2, SO_2 and dust significantly. The largest exergy destruction occurred in the boiler. Parallel co-firing offered better technical and environmental performances than direct co-firing.	[25]
-	Conventional	Electricity	-	32.26	-	To conduct an exergy analysis of a biomass * co-fired based conventional pulverized coal (bituminous and lignite) power plant. * chicken litter, pine sawdust, refuse-derived fuel and rice husks.	The largest exergy destruction occurred in the boiler, due to chemical reactions and heat transfer across a large temperature difference between the product gas and the feed water, with the combustor having the highest degree of destruction. The irreversibility rates of the plant decreased as the content of biomass in the fuel blend increased. However, the exergy efficiencies of the boiler and the overall plant decreased as the co-firing increased. Although biomass co-firing is not advantageous from a thermodynamic perspective, it helps reduce environmental emissions and enhances the finances of the plant.	[83]
1.0	Fluidized bed	Electricity	-	32.9	-	To apply the exergy method to the nine experimental results obtained from the pilot plant, modelled on bubbling fluidized bed co-combustion, using biomass * and low grade Spanish coal. * pine chips, i.e., wood waste.	The exergy destroyed ranged from 48.4% to 56.2% of the exergy input, with highest irreversibility found in the combustion process. The performance of the plant may be improved by reducing the exit temperature of the flue gas by the addition of a heat exchanger; heat loss to the environment can be reduced by insulating the combustion chamber.	[84]

5. Discussion

The performance assessment of energy from solid fuels used for generation of heat and power has been reviewed. An effective utilization of this energy in the heat and power plant is needed: as the fuel conversion efficiencies investigated are low. The use of energy efficiency to evaluate the performance of the system is not adequate as the energy method does not identify degradation of the energy quality during the energy conversion processes. As a result of this inaccuracy, the energy efficiencies are higher than the exergy efficiencies.

The difference between the energy and exergy efficiencies is observed in the heat and power plant, Figure 2, while little variation is seen in the power plant, Figure 3, where the data used is collected from Tables 1, 5 and 6. The produced heat, often distributed as water around 100 °C has a low energy quality (low exergy) but represents rather high energy content.

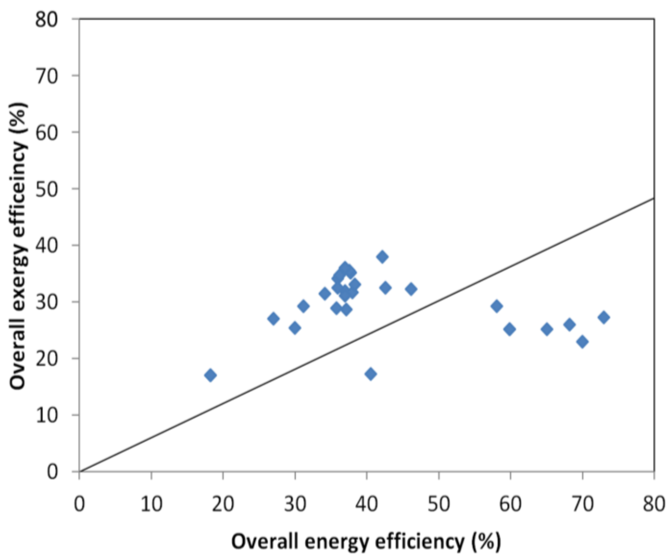

Figure 2. Variation of exergy and energy efficiency in different combined heat and power plants.

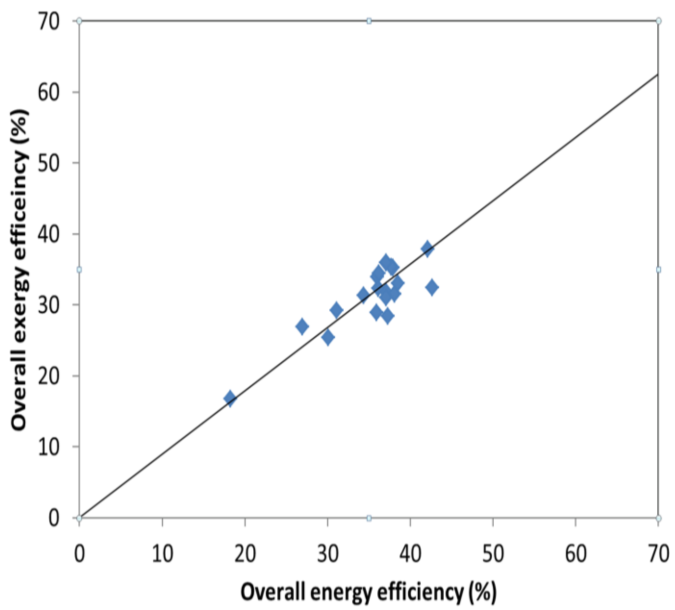

Figure 3. Variation of exergy and energy efficiency in different power plants.

The performance of the whole plant is based on the individual components of the system. Therefore, identification of the component with highest inefficiencies is the first step for performance improvement of the overall plant. According to the energy analysis, the major energy losses in a power plant are due to the heat rejection in the condenser as a result of the large enthalpy difference between the turbine and the condenser: here, second law analysis shows that less than 6% of the total exergy loss stems from the condenser while as much as 69% of the total energy loss is found in this component [62]. From the exergy analysis, the highest degree of exergy destruction occurs in the boiler (combustion and heat transfer) with over 50% of the total irreversibility in the plant. Figure 4 shows the effect of boiler efficiency on the performance of the overall plant, where the plant data is taken from Tables 1, 5 and 6. The result indicates that an increase in the boiler efficiency will increase the overall exergy efficiency of the plant.

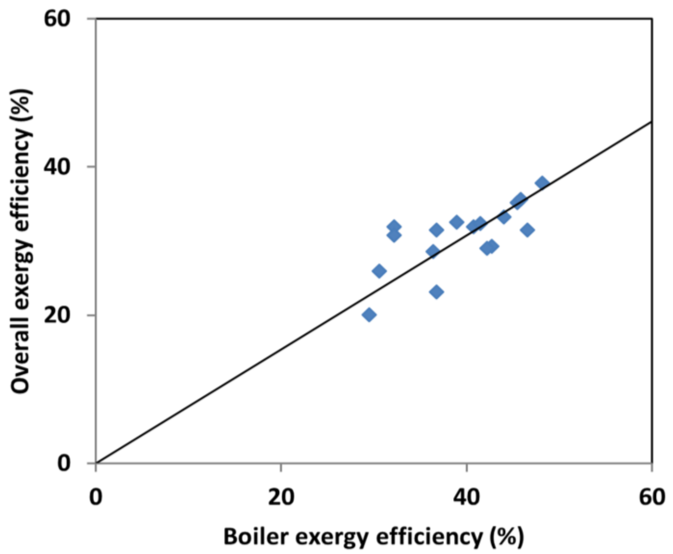

Figure 4. Effect of the boiler efficiency on the overall plant exergy efficiency.

The performance evaluations of the solid fuel-fired heat and power plants reviewed, shows in general, that the coal-fired plant has highest exergy efficiency compared with the other solid fuels. This is as a result of higher operating temperature and pressure. However, the CO_2 emissions associated with the system have an impact on the environment as a greenhouse gas. The emissions can be reduced by integrating the plant with carbon capture and storage [86]. But adopting this technology means extra cost and more energy is consumed during the process, which leads to reduction in the efficiency of the plant [47].

The biomass-based fuels on the other hand account for about 14% of the energy utilize in the world [87]. It remains the main source of energy for more than half of the world's population [88]. Although, biomass has a lower efficiency than coal; it is a suitable and renewable energy option that provides clean gas fuels presently and in the future [89,90].

Co-combustion of biomass and coal could decrease the consumption rate of coal as well as reduce the environmental impact from coal-fired plant. Biomass contains only a small amount of nitrogen and sulphur, which will reduce NO_2 and SO_2 emissions associated with coal [91]. Co-firing also gives higher exergy efficiency than the biomass-based plant. However, co-firing of biomass in the existing coal-fired plant decreases the boiler and overall exergy efficiency due to increased moisture content in the biomass, which reduces the furnace exit gas temperature [83]. Moreover, it increases corrosion and ash deposition in the system, and if co-utilization of biomass fuel in coal-fired plant is not carefully designed, it will involve risk of power outages [80].

Different improvement measures have been suggested by the past studies in order to reduce exergy destruction. Though excess air is needed for complete combustion, the amount should be minimized because an increase in excess air will reduce the adiabatic flame temperature and decrease the exergy efficiency of the boiler [67] as well as the overall exergy efficiency of the plant [53]. Installation of feedwater heaters will decrease the temperature difference of the flue gas and feedwater, and will reduce irreversibilities encountered in the boiler heat exchanger. The decrease in pressure of the condenser as well as increase in steam pressure and temperature will reduce exergy destruction and increase the overall system performance. However, increase in the temperature is limited by the boiler tube's oxidation temperature and allowable stress [67]. Moreover, the benefit of higher revenue as a result of increase in performance of the plant due to the increase in temperature and installation of feedwater heaters should be balanced against the increase in the capital cost to ensure that the pay-back period on the investment is favourable [23]. A plant operating at its full capacity is shown to be more economical and with higher exergy efficiency than those operating at part loads [52]. Because at full capacity, the heat absorbed in the combustion chamber will increase together with the efficiency of the boiler. However, this may not always be true for the combined heat and power plant: here, extraction ratio had a significant influence on the performance of the plant. As the plant with the smallest extraction ratio will have the highest exergy efficiency and lowest energy efficiency [42].

The use of advanced exergy-based method for evaluation of inefficiencies in the thermal conversion systems should be recommended. This method accounts for the avoidable and unavoidable exergy destruction associated with the plant and interaction between the components. The unavoidable part of exergy destruction cannot be improved, even using the best possible solution with available technology [44], as a result of limitation in the design specifications of the plant. The efforts to improve the plant should then be concentrated on the avoidable part so that the real thermodynamic inefficiencies and their causes can be identified [92].

6. Conclusions

Exergy analysis is a reliable method that can be used for the design, optimization, performance evaluation and calculation of efficiency of a solid fuel-fired heat and power plant. The exergetic method enables the main sources of loss to be identified, quantifies the irreversibilities that result from the entropy generated and provides direction for improving performance in the system. The application of exergy analysis should be extended to biomass-based and biomass co-combustion fired power plants so that important improvements can be made, because limited research work has been carried out in these sectors. Turkey and India are the two major countries where exergy analysis has been applied to solid fuel power plants, the majority of which are coal-fired. The results of the present review indicate that extensive research should focus on the combustion and heat transfer processes in boilers in order to optimise the performance of solid fuel-fired heat and power plants.

Acknowledgments: Financial support from University of Borås, Sweden and TETFund Nigeria through Michael Okpara University of Agriculture, Umudike, Abia State, Nigeria is greatly appreciated.

Author Contributions: Francis Chinweuba Eboh is responsible for the literature survey and writing of the manuscript. Peter Ahlström and Tobias Richards supervised the research work.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

$\dot{E}$	energy rate (kW)
$\dot{E}x$	exergy rate (kW)
ex	specific exergy (kJ/kg)
h	specific enthalpy (kJ/kg)
$\dot{I}$	irreversibility rate or exergy destruction rate (kW)

$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (kW)
$\dot{S}$	entropy rate (kW/K)
s	specific entropy (kJ/kgK)
T	temperature (K)
$\dot{W}$	work transfer rate (kW)
Subscripts	
a	air
f	fuel
fg	flue gas
hp	hot product
L	lost
p	product
pl	plant
e	exit
o	out
gen	generation
i	input
0	reference environment or dead state
Superscripts	
Ch	chemical
Ke	kinetic energy
Pe	potential energy
Ph	physical
Abbreviations	
B	boiler
C	combustor
CEP	condensate extraction pump
CFWH	closed feed water heater
CHP	combined heat and power
Cond	condenser
FP	feed water pump
HE	heat exchanger
HPT	high pressure turbine
IPT	intermediate pressure turbine
LPT	low pressure turbine
OFWH	open feed water heater
HP	hot product
WTP	waste-to-energy
Greek letter	
η	efficiency

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