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Exergy Efficiency and Environmental Impact of Electricity of a 620 MW-Natural Gas Combined Cycle

Muna Hamad Almansoori, Zin Eddine Dadach*

Chemical & Petroleum Engineering Department, Abu Dhabi Men's College, Higher Colleges of Technology, Abu Dhabi, UAE
Email: *zdadach@hct.ac.ae

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Abstract

In the first part of this investigation, a Natural Gas Combined Cycle (NGCC) producing 620 MW of electricity was simulated using the commercial software Aspen Hysys V9.0 and the Soave-Redlich-Kwong (SRK) equation of state. The aim of this second part is to use exergy-based analyses in order to calculate its exergy efficiency and evaluate its environmental impact under standard conditions. For the exergy efficiency, the performance index under investigation is the exergy destruction ratio (y_D). The results of the study show that the combustor is the main contributor to the total exergy destruction of the power plant (y_D = 24.35%) and has the lowest exergy efficiency of 75.65%. On the other hand, the Heat Recovery Steam Generator (HRSG) has the lowest contribution to the exergy destruction (y_D = 5.63%) of the power plant and the highest exergy efficiency of 94.37%. For the overall power plant, the exergy efficiency is equal to 53.28%. For the environmental impact of the power plant, the relative difference of exergy-related environmental impacts (r_b) is utilized as the performance index for each equipment of the plant and the environmental impact of a kWh of electricity (*EIE*) is used to represent the performance index of the overall power plant. In agreement with the exergy analysis, the results indicate that the combustor and the HRSG have respectively the highest (r_b = 32.19%) and the lowest (r_b = 5.96%) contribution to the environmental impact. The environmental impact of a kWh of electricity of the power plant is 34.26 mPts/kWh (exergy destruction only), and 34.42 mPts/kWh (both exergy destruction and exergy loss).

Keywords

Exergy Analysis, NGCC Power Plant, Life Cycle Impact Assessment (LCIA) Method, Environmental Impact of Electricity

1. Introduction

The Government of the UAE aspires to reduce CO_2 emissions by capturing carbon dioxide from industrial emitters and transporting the CO_2 to oilfields for Enhanced Oil Recovery (EOR). In order to demonstrate and test this concept, Abu Dhabi Company for Onshore Oil Operations (ADCO) recently implemented a pilot-scale CO_2 Enhanced Oil Recovery in one of its onshore oil fields. This is the first CO_2-EOR flood implemented in the Middle East [1]. To provide a large volume of CO_2 needed for EOR projects in the UAE, CO_2 is captured from all its industrial facilities such as power & desalination plants, oil refineries, gas processing facilities and petrochemical complexes.

Gas-fired power generation plants with Carbon Capture and Storage (CCS) are expected to play a significant role in order to reduce carbon dioxide emissions from the power generation sector. Because of the complementary temperature ranges of the Brayton GT cycle and the Rankine steam cycle, natural gas combined cycle (NGCC) can produce significantly improved thermodynamic cycle efficiency [2]. Natural gas is the recommended combustible for future CCS projects because it reduces the operating cost of the plants by avoiding corrosion and other technical problems in the facilities and reservoirs due to the impurities (H_2S, SOx, NOx, HCl …). However, the corresponding molar percentage of CO_2 in flue gas is about 3% - 3.5% [3]. On the other hand, for an effective CO_2 capture by amine solutions, it is recommended to obtain a molar percentage of CO_2 in the flue gas around 10% - 15% [4]. The cost of CO_2 capture from natural gas fired power generation plants is therefore high due to the fact that a large amount of energy is needed in the stripper in order to obtain leaner amine solutions needed for the lower concentrations of carbon dioxide in the flue gas. High Flue Gas Recirculation (FGR) ratios are therefore needed in order to increase the CO_2 concentration in the flue gas to be treated in the absorption unit. The recirculated flue gas is utilized as the secondary air (dilution air) to cool down the blades of the turbine.

The real plant inefficiencies of energy conversion systems are not related to heat loss but to irreversibilities in the process. An exergy analysis is therefore recommended for power generation plants in order to calculate the exergy destruction caused by the irreversibilities in each equipment of the plant. By evaluating the exergy destroyed in each component in the plant, efforts will be focused on the equipment that presents the highest exergy destruction because it will offer the largest improvement of the exergy efficiency of the process. As a consequence, the fuel consumption and environmental impact of the plant are also reduced. Based on an exergy analysis around a 180 MW-NGCC power plant in Sudan [5], the percentages of exergy destruction of the different parts of the plant were respectively: Combustor (63%), GT (13.6%), ST (6.4%), HRSG (4.7%), Exhaust gas (3.8%), Compressors (3.8%) and cooling systems (2.3%). An exergy analysis conducted around an NGCC power plant in Nigeria also indicates that the combustion chamber is the most exergy destructive component compared to other cycle components. The percentage of exergy destruction in combustion chamber varied between 86.05% and 94.6% [6].

In our previous investigation, an exergy analysis was conducted around a 160 MW-Open Cycle Gas Turbine (OCGT) in Abu Dhabi (UAE) in order to study the effects of summer weather conditions on the performance of the plant. The software Aspen Hysys V8.6 with the Soave-Redlich-Kwong (SRK) equation was used to simulate the power plant using standard operating conditions. The results indicated that the combustion chamber was the main factor (70.2%) of the total exergy destruction of the plant. On the other hand, the compressor had the lowest exergy destruction (12.4%). From the design conditions, results show that, during summer weather conditions, the power plant lost 7.6 MW (4.66%) and 4.61% of its exergy efficiency [7].

The final objective of increasing exergy efficiency of power plants is to reduce the consumption of fuel in order to minimize its environmental impact. The exergoenvironmental analysis of power generation plants is conducted in three steps: 1) an exergetic analysis, 2) a Life Cycle Assessment (LCA) and 3) the assignment of environmental impacts to all of the material streams of the system [8]. Based on this methodology, Morosuk *et al.* [9] conducted an exergoenvironmental analysis with five different indicators (ECO-95, ECO-99, CExC, CML and ECO-F2006) around a cogeneration plant based on an open-cycle gas-turbine power system. The results show that the environmental impact of many energy conversion systems could be improved simply by improving their thermodynamic efficiency. Moreover, Petrakopoulou *et al.* [10] investigated the environmental impact of a three-pressure level combined cycle power plant. The calculated value of the environmental impact of electricity (14.69 mPts/kWh) was lower than the average value 27 mPts/kWh for power plants in Europe [8]. When including the formation of pollutants in the calculations, the value increased to 25.1 mPts/kWh [11]. Açıkkalp *et al.* [12] estimated the environmental impact per kWh of produced electricity of a combined cycle power plant to be 30.5 mPts/kWh at 284 K.

Following the investigation on an exergy analysis of an Open Cycle Gas Turbine in Abu Dhabi (UAE), the effects of summer weather conditions on the environmental impact of the power plant were investigated in a second investigation using an exergoenvironmental analysis [13]. The results indicate that the main contributor to the environmental impact of exergy destruction was the combustor. Summer weather conditions increased its impact by 21.5%. The compressor had the second highest environmental impact, increased by 14.6% for summer weather conditions. The environmental impact of a kWh of electricity during summer weather conditions was 40.3 mPts/kWh (exergy destruction only) and 59.0 mPts/kWh (including the exergy loss). The corresponding values related to the standard weather conditions are 37.8 mPts/kWh and 54.7 mPts/kWh, respectively.

A 620 MW-Natural Gas Combined Cycle (NGCC) power generation plant using 100% excess air was simulated in the first part of this investigation [14]. In order to have a composition of the exhaust gas suitable for an effective absorption by amine solutions, an optimum value of a Flue Gas Recirculation (FGR) ratio of 0.42 was calculated. As a result, the molar percentage of carbon dioxide in the flue gas increased from 5% to 9.2% and the molar percentage of oxygen decreased from 10.9% to 3.5%. Moreover, based on the low heating value (*LHV*) of the natural gas, the flue gas recirculation also increased the overall efficiency of the power plant by 1.1% from 57.5% to 58.2%. The objective of this second part of the investigation is to calculate the exergy efficiency (*EE*) of the NGCC power plant and evaluate its environmental impact of electricity (*EIE*) under standard conditions.

2. Methodology

2.1. Concept of Exergy

Exergy is commonly described as the theoretical (*maximum*) *work that can be obtained from a system under investigation and its* "*environment*". *It is assumed that the system passes from an initial state to a state of equilibrium with the environment* [15]. *When a system becomes in equilibrium with its environment, the state of the system is called* "*dead state*" *and its exergy is equal to zero. Based on Equation* (1), *total exergy* (E_T) *of a stream is composed of four main elements* [16]:

$$E_T = E_{ph} + E_{Ch} + E_k + E_p \tag{1}$$

The physical exergy (E_{ph}) part is defined as the useful (theoretical) work produced as the system passes from its initial state (P, T) to the "restricted dead state" (P_0, T_0). The chemical exergy (E_{ch}) part is defined as the useful work obtained when the system passes from the "restricted dead state", where only the conditions of mechanical and thermal equilibrium are satisfied, to the "dead state" where it is in complete equilibrium with the environment [17]. The kinetic (E_k) and potential (E_p) parts of the total exergy are associated to the system velocity and height, respectively measured relative to a given reference point. When a system is at rest relatively to the environment ($E_k = E_p = 0$), the total mass specific exergy (e_T) of a stream is defined as [16]:

$$e_T = e_{ph} + e_{Ch} \tag{2}$$

2.2. Standard Chemical Exergy of a Gas Mixture

The chemical exergy per mole of gas (k) is defined as [16]:

$$e_{Ch}^k = -R \cdot T \cdot \ln x_e^k \tag{3}$$

For a mixture of gases, the total chemical exergy per mole of the mixture is given by [16]:

$$e_{Ch} = \sum x_k \cdot e_{Ch}^k + R \cdot T \cdot \sum x_k \cdot \ln x_k \tag{4}$$

The values of exergy of different hydrocarbons and other components are listed in the literature [15]. The chemical exergy of a fuel could be estimated using Equation (4). It should be noted that the value of the specific chemical exergy of a fuel at dead-state conditions is between the lower (*LHV*) and higher (*HHV*) heating values of the fuel [16].

2.3. Exergy Balance in Open Systems

Based on the second law of thermodynamics, exergy is not conserved in any real process. An exergy balance must therefore contain a "destruction" term, which vanishes only for a reversible process. The general form of exergy balance for a control volume could be written as [16]:

$$\frac{\mathrm{d}E_{CV}}{\mathrm{d}t} = \Sigma E_{heat} + E_{work} + \Sigma m_i \cdot e_{T,i} - \Sigma m_e \cdot e_{T,e} - E_D \quad (5)$$

For a steady state system, Equation (5) could be rewritten as:

$$0 = \Sigma E_{heat} - W_{cv} + \Sigma m_i \cdot e_{T,i} - \Sigma m_e \cdot e_{T,e} - E_D \quad (6)$$

In Equation (6), the total specific exergy transfer at the inlets and outlets could be written as:

$$e_T = (h - h_0) - T_0 (s - s_0) + \sum x_k \cdot e_{Ch}^k + R \cdot T \cdot \sum x_k \cdot \ln x_k \quad (7)$$

where h and s are properties at the inlet and the outlet of the system. h_0 and s_0 are respectively the specific enthalpy and the specific entropy of the restricted dead state.

2.4. Exergy Analysis

A process flow diagram (PFD) of a natural gas combined cycle (NGCC) is shown in **Figure 1**. The main equipment of the process are: compressor (K), combustor (CC), combustion turbine generator (CTG), steam turbine generator (STG), heat recovery steam generator (HRSG), condenser (C) and pump (P).

Following the process described in **Figure 1**: 1) fresh air enters the compressor in which it is compressed to higher pressure. 2) The compressed air leaves the compressor at higher pressure. In the combustor (CC), combustion takes

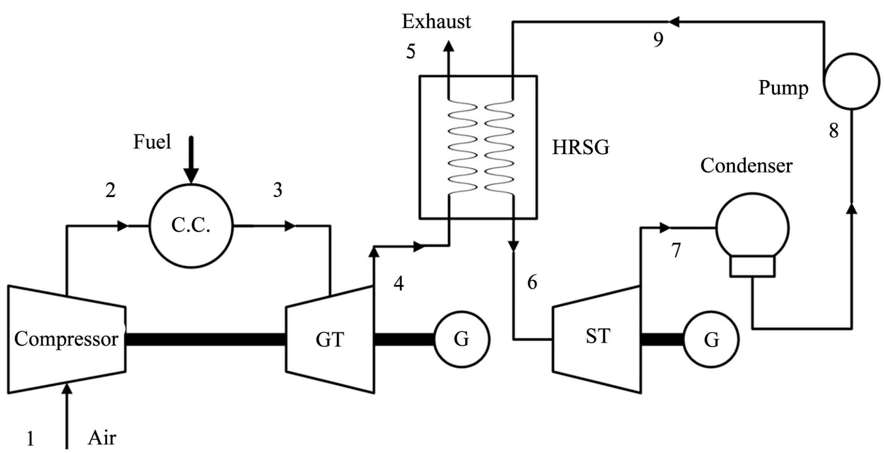

Figure 1. Schematic representation of natural gas combined cycle [14].

place between the compressed air and the natural gas. 3) The exhaust gas leaves the combustor and enters the gas turbine generator (GT) where the flue gas is expanded to generate electricity. 4) The flue gas leaves the turbine at high temperature. This first cycle of the natural gas combined cycle is known as the Brayton cycle. 5) In the second cycle of the power plant, the heat of the hot flue gas is utilized in the heat recovery steam generator (HRSG) to produce high pressure steam. As a consequence, he flue gas leaves the HRSG at lower temperature. 6) High pressure steam produces electricity in the steam turbine generator (STG). 7) Steam leaving the STG is condensed in a heat exchanger, and 8) the water is pumped to higher pressure. 9) High pressure water reenters the Rankine cycle.

Appling the exergy analysis of the NGCC power plant described in **Figure 1**, the exergy destruction (*ED*) and exergy efficiency (*EE*) for the seven main components of a natural gas combined cycle (NGCC) are estimated using the following equations [16] [17] [18]:

Compressor (AK)

$$(ED)_{AK} = W_{AK} - m_{air}(ex_2 - ex_1) \tag{8}$$

$$(EE)_{AK} = 1 - \frac{(ED)_{AK}}{(EF)_{AK}} \tag{9}$$

Combustor (CC)

$$(ED)_{CC} = (m_{air} \times ex_3) + (m_{fuel} \times ex_{fuel}) - (m_{fg} \times ex_6) \tag{10}$$

$$(EE)_{CC} = 1 - \frac{(ED)_{CC}}{(EF)_{CC}} \tag{11}$$

Gas Turbine (GT)

$$(ED)_{GT} = m_{fg}(ex_8 - ex_9) - WGT \tag{12}$$

$$(EE)_{GT} = 1 - \frac{(ED)_{GT}}{(EF)_{GT}} \tag{13}$$

Heat Recovery System Generator (HRSG)

$$\begin{aligned}(ED)_{HRSG} = {} & (m_9 \times ex_9) + (m_{21} \times ex_{21}) + (m_{23} \times ex_{23}) + (m_{25} \times ex_{25}) \\ & - (m_{10} \times ex_{10}) - (m_{22} \times ex_{22}) - (m_{24} \times ex_{24}) - (m_{20} \times ex_{20})\end{aligned} \tag{14}$$

$$(EE)_{HRSG} = 1 - \frac{(ED)_{HRSG}}{(EF)_{HRSG}} \tag{15}$$

Pump (P)

$$(ED)_P = W_p + m_{20}(ex_{20} - ex_{21}) \tag{16}$$

$$(EE)_P = 1 - \frac{(ED)_P}{(EF)_P} \tag{17}$$

Compressor (RK)

$$(ED)_{RK} = W_{RK} + m_{13}(ex_{10} - ex_{18}) \tag{18}$$

$$(EE)_{RK} = 1 - \frac{(ED)_{RK}}{(EF)_{RK}} \tag{19}$$

Steam Turbine (ST)

$$(ED)_{ST} = m_{20}\left(ex_{22} + ex_{24} + ex_{26} - ex_{23} - ex_{25} - ex_{27}\right) - WHP - WIP - WLP \tag{20}$$

$$(EE)_{ST} = 1 - \frac{(ED)_{ST}}{(EF)_{ST}} \tag{21}$$

Based on the definitions of exergy rates associated with fuel $\left(\hat{E}_{F,k}\right)$ and product $\left(\hat{E}_{P,k}\right)$ [16], the rate of fuel exergy and product exergy of the seven main components are given in **Table 1**.

The rate of exergy destruction within the k^{th} component, $(ED)_k$, is calculated as the difference between its rate of fuel and product exergy [16]:

$$(ED)_k = \hat{E}_{F,k} - \hat{E}_{P,k} \tag{22}$$

And the exergy destruction ratio in each equipment could be written as [16]:

$$Y_{D,K} = 100 \cdot \frac{(ED)_k}{\hat{E}_{F,k}} \tag{23}$$

The exergy balance and exergetic efficiency of the overall power plant are [16]:

$$\hat{E}_{F,total} = \hat{E}_{P,total} + \widehat{ED}_{total} + \hat{E}_{L,total} \tag{24}$$

$$(EE)_{total} = 1 - \frac{\widehat{ED}_{total} + \hat{E}_{L,total}}{\hat{E}_{F,total}} \tag{25}$$

2.5. Exergoenvironmental Analysis

The environmental impact of power generation plants is directly linked to the amount of fuel consumed. In this perspective, an exergoenvironmental analysis is very powerful tool in order to detect the relative effect of each component of the process, with respect to environmental impact. In this analysis, a one-dimensional characterization indicator (Eco-indicator) is obtained using a Life Cycle Assessment (LCA). LCA is a technique used to quantify the environmental impact of inputs (resources) and outputs (products, pollutants, etc.) of systems relative to the natural use of resources, human health and other ecological areas. The quantification of the environmental impact caused by depletion and emissions of a natural resource used can be carried out using [19]:

1) Life Cycle Assessment following ISO 14044,
2) Matrix-based LCA,
3) Proxy measures.

Proxy measures are based on a single value to describe the environmental impact of a product or material. One of commonly used Proxy measure is the life cycle impact assessment (LCIA) method Eco-indicator. The Eco-indicator of a material or a process is a number that represents its environmental impact based on data from a life cycle assessment. A higher the indicator indicates a greater

Table 1. Rate of fuel and product exergy for each component.

Equipment	$\hat{E}_{F,k}$ (MW)	$\hat{E}_{P,k}$ (MW)
Compressor (AR)	W_{Ak}	$m_1(ex_1 - ex_2)$
Combustor (CC)	$(m_4 \times ex_4) + (m_3 \times ex_3)$	$(m_6 \times ex_6)$
Gas Turbine (GT)	$m_8(ex_8 - ex_9)$	W_{GT}
Heat Recovery System Generator (HRSG)	$m_9(ex_9 - ex_{10})$	$m_{20}(ex_{22} + ex_{24} + ex_{26} - ex_{21} - ex_{23} - ex_{20})$
Pump (P)	W_p	$m_{20}(ex_{21} - ex_{20})$
Compressor (RK)	W_{RK}	$m_{13}(ex_{10} - ex_{13})$
Steam Turbine (ST)	$m_{20}(ex_{22} + ex_{24} + ex_{26} - ex_{23} - ex_{25} - ex_{27})$	$W_{HP} + W_{IP} + W_{LP}$
NGCC	$m_{fuel} \cdot ex_{Fuel}$	$W_{NET-OUT}$

environmental impact of the process. LCIA methods, like Eco-indicator 95 [20], Eco-indicator 99 [8] and the Swiss Ecoscarcity [21] have been successfully utilized for energy conversion systems.

Eco-indicator 99 has been utilized by some researchers [10] [11] [12] [22] to test its suitability in LCA-related issues and several LCA software packages support it (e.g., SimaPro and Gabi) [23]. According to **Figure 2**, the Eco-indicator 99 defines three categories of damage (end points): human health, ecosystem quality and depletion of resources. The quantification of inputs and outputs of systems is called Life Cycle Inventory (LCI). The objective of LCIA is to convert these flows into simpler indicators. Based on this methodology, the environmental impact rate B_j of the j-th material stream is estimated using its specific exergy ex_j, mass flow rate m_j and specific environmental impact b_k [9]:

$$B_j = E_j \cdot b_j = m_j \cdot e_j \cdot b_j \tag{26}$$

B_j is defined as the Eco-indicator points per unit of time (Pts/s or mPts/s). The specific exergy-based environmental impact b_j is the average value of the environmental impact associated with the production of the stream per unit of exergy of the same stream [Pts/(GJ exergy) or mPts/(GJ exergy)] [12]. Using the physical and chemical components of the specific exergy, the environmental impact rate B_j can be written as [9]:

$$B_j = m_j \cdot e_{Ph} \cdot b_{Ph} + m_j \cdot e_{Ch} \cdot b_{Ch} = m_j \cdot b_j \tag{27}$$

The environmental impact rates associated with heat Q and work W streams are calculated as [9]:

$$B_Q = b_Q \cdot E_Q \tag{28}$$

$$B_W = b_W \cdot E_W \tag{29}$$

The exergy rate associated with heat transfer is calculated using the following equation [9]:

$$E_Q = \left(1 - \frac{T_0}{T_k}\right) \cdot Q \tag{30}$$

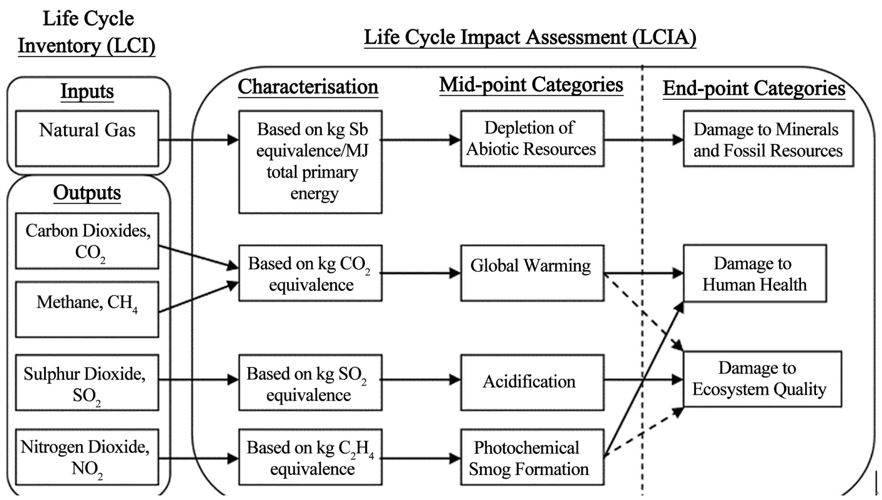

Figure 2. Typical LCA framework linking LCI via mid-point categories to end-point categories for selected damage types [21].

where, T_0 is the ambient temperature and T_k the temperature at which the heat transfer crosses the boundary of the system. The objective of environmental impact balances is to calculate the environmental impact $B_{j,out}$ of all streams exiting each individual process. The environmental impact balance for the k-th component of a power plant states that the sum of environmental impacts associated with all input streams plus the component-related environmental impact is equal to the sum of the environmental impact of all output streams [9]:

$$\sum_{j=1}^{n} B_{j,k}^{in} + Y_k = \sum_{j=1}^{m} B_{j,k}^{out} \tag{31}$$

The component-related environmental impact of the k-th component of the plant (Y_k) includes the three life-cycle phases of construction ($Y_{CO,k}$) (manufacturing, transport and installation), the operation and maintenance ($Y_{OM,k}$) and the disposal ($Y_{DI,k}$) [9]:

$$Y_k = Y_{CO,k} + Y_{OM,k} + Y_{DI,k} \tag{32}$$

Using data of the exergy analysis and LCA, the specific environmental impact b_k is calculated as:

$$b_{k,in} = \frac{B_{k,in}}{E_{k,in}} \tag{33}$$

As shown in **Table 2**, the first step of the exergoenvironmental analysis is to determine the environmental impact of each stream by solving the environmental impact balance of the main components of the power plant [16].

The second step of the exergoenvironmental analysis is to determine the environmental impact rates of product and fuel, $B_{P,k}$ and $B_{F,k}$ of each equipment (k) of the process. These environmental impact rates are shown in **Table 3** [16].

The rate of exergy destruction within the k^{th} component, $(ED)_k$, is calculated as the difference between its rate of fuel and product exergy [16]:

Table 2. Environmental impact balances for the main components.

Equipment	Environmental Impact Balance		Auxiliary Equations	
Compressor (AK)	$b_2 \cdot E_2 = b_1 \cdot E_1 + b_{AK} \cdot W_{AK} + Y_{AK}$	(34)	$b_1 = 0$ (fresh air)	(35)
Mix-100	$b_5 \cdot E_5 = b_3 \cdot E_3 + b_{4,fuel} \cdot E_{4,fuel} + Y_{Mix-100}$	(36)	$b_2 = b_7 = b_3$	(37)
Combustor (CC)	$b_6 \cdot E_6 = b_5 \cdot E_5 + B_{CC}^{PF} + Y_{CC}$	(38)	b_{fuel} and $b_{CO_2}^{PF}$	(39)
Mix-101	$b_8 \cdot E_8 = b_{18} \cdot E_{18} + b_7 \cdot E_7 + b_6 \cdot E_6 + Y_{Mix-101}$	(40)		
Gas Turbine (GT)	$b_9 \cdot E_9 + b_{GT} \cdot W_{GT} = b_8 \cdot E_8 + Y_{GT}$	(41)	$b_8 = b_9$	(42)
			$b_{AK} = b_{RK} = b_{GT} = b_{ST} = b_P$	(43)
HRSG + ST	$b_{10} \cdot E_{10} + b_{27} \cdot E_{27} + b_{ST} \cdot W_{ST} = b_9 \cdot E_9 + b_{21} \cdot E_{21} + Y_{HRSG}$	(44)	$b_{20} = b_{21} = b_{27}$	(45)
			$b_{10} = b_{13}$	(46)
Pump	$b_{21} \cdot E_{21} = b_{20} \cdot E_{20} + b_P \cdot W_P + Y_P$	(47)		
Compressor (RK)	$b_{18} \cdot E_{18} = b_{13} \cdot E_{13} + b_{RK} \cdot W_{RK} + Y_{RK}$	(48)		

Table 3. Environmental impact rate of fuel and product for the components of the power plant.

Equipment	Environmental impact rate of fuel $B_{F,k}$ (mPts/s)	Environmental impact of product $B_{P,k}$ (mPts/s)
Compressor (AR)	$b_{AK} \cdot W_{AK}$	$b_2 \cdot E_2 - b_1 \cdot E_1$
Combustor (CC)	$b_5 \cdot E_5 + b_{4,fuel} \cdot E_{4,fuel} + B_{CC}^{PF}$	$b_6 \cdot E_6$
Gas Turbine (GT)	$b_8 \cdot E_8 - b_9 \cdot E_9$	$b_{GT} \cdot W_{GT}$
Heat Recovery System Generator (HRSG)	$b_9 \cdot E_9 - b_{10} \cdot E_{10}$	$b_{24} \cdot E_{24} + b_{22} \cdot E_{22} + b_{20} \cdot E_{20} - b_{23} \cdot E_{23} - b_{25} \cdot E_{25} - b_{21} \cdot E_{21}$
Pump (P)	$b_P \cdot W_P$	$b_{21} \cdot E_{21} - b_{20} \cdot E_{20}$
Compressor (RK)	$b_{RK} \cdot W_{RK}$	$b_{18} \cdot E_{18} - b_{13} \cdot E_{13}$
Steam Turbine (ST)	$b_{22} \cdot E_{22} - b_{27} \cdot E_{27}$	$b_{ST} \cdot W_{ST}$
NGCC	$b_{F,NGCC} \cdot E_{4,fuel}$	$b_{p,NGCC} \cdot W_{NET-OUT}$

$$\left(ED\right)_k = \hat{E}_{F,k} - \hat{E}_{P,k} \tag{49}$$

The total environmental impact associated with component k includes the environmental impact of exergy destruction $B_{D,k}$ and the component-related environmental impact Y_k. In the case of the reactors, an additional term related to pollutant formation (PF) is added. Here, the environmental impact of pollutant formation (B_k^{PF}) is added to the combustor because it represents the account of pollutants formation such as CO, CO_2, CH_4, NO_x and SO_x [9].

$$B_{P,k} = B_{F,k} + Y_k + B_k^{PF} \tag{50}$$

Here, the pollutant formation is determined by the formed CO_2 emissions [9]:

$$B_{CC}^{PF} = b_{CO_2}^{PF} \cdot \left(m_{CO_2,out} - m_{CO_2,in}\right) \tag{51}$$

The average exergy-based specific environmental impact of product and fuel for the k^{th} component are [9]:

$$b_{P,k} = \frac{B_{P,k}}{\hat{E}_{P,k}} \quad (52)$$

$$b_{F,k} = \frac{B_{F,k}}{\hat{E}_{F,k}} \quad (53)$$

The environmental impact of exergy destruction $B_{D,k}$ of each k^{th} component of the power plant is calculated by multiplying the specific environmental impact of the fuel and the exergy destroyed in the equipment [9]:

$$B_{D,k} = b_{F,k} \cdot E_{D,k} \quad (54)$$

The combination of exergy and exergoenvironmental analyses identify the components with the highest environmental impact in order to propose the possibilities and trends for improvement, and decrease the environmental impact of the overall plant. This objective can be achieved by using the relative environmental impact difference ($r_{b,k}$) [9]. The environmental impact difference ($r_{b,k}$) of the k-th component of the power plant depends on the environmental impact of its exergy destruction ($B_{D,k}$) and its component-related environmental impact (Y_k) [9]:

$$r_{b,k} = \frac{1 - EE}{EE} + \frac{Y_k + B_k^{PF}}{B_{D,k}} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} \quad (55)$$

Neglecting (Y_k) effects of the plant site on the environment

$$r_{b,k} = \frac{E_{D,k}}{E_{P,k}} \quad (56)$$

$r_{b,k}$ is an indicator of the reduction potential of the environmental impact associated with the component. In general, a relatively high value of $r_{b,k}$ indicates that the environmental impact of the corresponding component can be reduced with a smaller effort than the environmental impact of a component with a lower value. Independently of the absolute value of the environmental impacts, the relative difference of specific environmental impacts represents the environmental quality of a component. The environmental impact of electricity (*EIE*) of the Natural Gas Combined Cycle (NGCC) could then be estimated using the environmental impact balance applied to the overall system [9]:

$$EIE = \frac{3.6 \cdot \left(b_{F,tot} \dot{\hat{E}}_{F,tot} + \dot{Y}_{tot} + \dot{B}_{tot}^{PF} \right)}{\dot{\hat{E}}_{P,tot}} \quad (57)$$

When the environmental impact associated with the exergy losses of the overall system is charged to the product, we obtain [9]:

$$EIE = \frac{3.6 \cdot \left(b_{F,tot} \dot{\hat{E}}_{F,tot} + \dot{Y}_{tot} + \dot{B}_{tot}^{PF} + B_{L,tot} \right)}{\dot{\hat{E}}_{P,tot}} \quad (58)$$

3. Power Plant Evaluation

3.1. Process Description

As shown in **Figure 3**, a 620 MW-natural gas combined cycle (NGCC) with a flue gas recirculation ratio of 0.42 was simulated in the first part of this study [14]. A mass flowrate of 23.81 kg/s of natural gas, which consists of 93 mol% methane, is meant to be available in a battery limit of the plant at 3.1 MPa and 25˚C. 447.7 kg/s of fresh air at design atmospheric condition is compressed up to 3.1 MPa in a three stages compressor with intercooling.

In the combustion chamber, natural gas mixes with primary air and it is assumed complete combustion where all the carbon element of the natural gas is turned into carbon dioxide. Based on the first part of this investigation [14], the temperature of the combustion gases is 2100˚C. Secondary air is mixed with recirculated flue gas to reduce its temperature to 1300˚C before entering the turbine [14].

The exhaust gases leave the gas turbine at atmospheric pressure and 618˚C. The flue gas enters the heat recovery steam generator (HRSG) to produce 119 kg/s of steam at three pressure levels: high pressure (HP) steam (173 bar, 600˚C), intermediate pressure (IP) steam (65 bar, 565˚C), and low pressure (LP) steam (1 bar, 350˚C) with double reheat. The medium pressure steam (IP) is heated from 438˚C to 565˚C and low-pressure steam (LP) is heated from 100˚C to 350˚C [14].

After leaving the heat recovery steam generator (HRSG), the flue gas is cooled from 66.5˚C to 40˚C to remove water using the separator V-100 and 42% of the flue gas is recycled. The pressure of the recycled gas will increase from 110 kPa to 3.1 MPa using three stages compressor with intercooling at 40˚C and mixed with secondary ambient air [14].

3.2. Operating Conditions and Specific Exergy of the Different Streams of the Process

From the simulated NGCC power plant (**Figure 3**) [14], the operating conditions and the specific exergy of each stream are shown in **Table 4**.

3.3. Exergy Analysis

The values of the exergy destruction and the exergy efficiency of each component of the power plant are obtained by solving the set of Equations (8)-(21). The rates of fuel and product exergy for each component are calculated by solving equations in **Table 1**. The final results of the exergy analysis are shown in **Table 5**.

3.4. Exergoenvironmental Analysis

The values of the specific environmental impact of carbon dioxide and the depletion of fuel in Eco-99 points were taken from literature [9]:

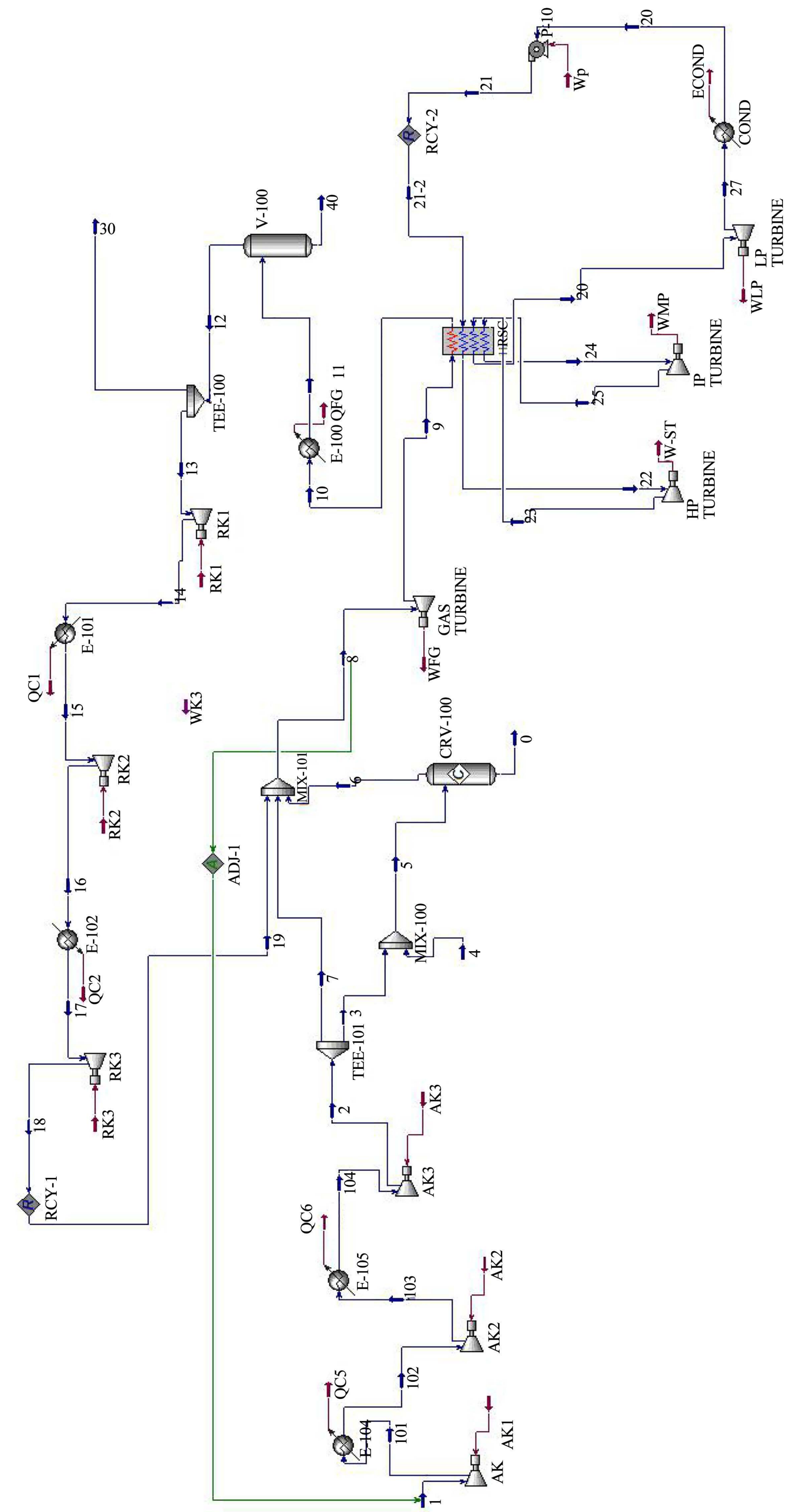

Figure 3. Simulated natural gas combined cycle power plant.

Table 4. Stream-level operating conditions.

Stream No	Temp. (˚C)	Pressure (bar)	Mass Flow (kg/s)	Specific Exergy (kJ/kg)
1	15	1.0132	447.74	0 (dead state)
2	190	31	447.74	329.45
3	190	31	384.53	329.45
4	25	31	23.81	49,410.92
5	170	31	408.34	335.16
6	2099	31	408.34	2398.25
7	190	31	63.21	329.45
8	1303	31	793.02	1293.85
9	618	1.1	793.02	328.11
10	67	1.1	793.02	17.41
11	40	1.1	793.02	8.52
12	40	1.1	762.11	8.80
13	40	1.1	320.09	8.80
18	222	31	320.09	343.12
20	30	0.07	118.67	0.06
21	32	173	118.67	23.10
22	600	173	118.67	1590.16
23	438	65	118.67	1295.16
24	565	65	118.67	1479.02
25	100	1	118.67	475.48
26	350	1	118.67	683.89
27	61	0.07	118.67	115.98
30	40	1.1	442.03	8.80
40	40	1.1	30.90	1.63

Table 5. Component-level exergy results.

Equipment	$\hat{E}_{D,k}$ (MW)	$\hat{E}_{D,k}$ (%)	$\hat{E}_{F,k}$ (MW)	$\hat{E}_{P,k}$ (MW)	$y_{D,k}$	$\hat{E}_L$ (MW)	EE_k (%)
Compressor (AK)	26.71	5.85	174.22	147.51	15.33		84.67
Combustor (CC)	**315.20**	**69.03**	**1294.49**	**979.29**	**24.35**		**75.65**
Gas Turbine (GT)	57.37	12.56	765.85	708.48	7.49		92.51
Heat Recovery Steam Generator (HRSG)	13.87	3.04	246.39	232.52	5.63		94.37
Pump (P)	0.41	0.09	3.15	2.73	13.09		86.91
Compressor (RK)	21.63	4.74	125.88	104.26	17.18		82.82
Steam Turbine (ST)	21.44	4.69	235.26	213.82	9.11		90.89
NGCC	**456.62**	**100.00**	**1167.81**	**622.20**	**92.19**	**3.93**	**53.28**

Global warming (kg(CO_2-eq.)/kWh): This indicator measures the total quantity of greenhouse gases (GHG) released to the atmosphere from the power plant. The value of the specific environmental impact of CO_2 for Eco-99 is equal to 5.454 mPts/kg.

Depletion of fossil fuel: This indicator measures the total primary energy in fossil resources used for the production. When no pollutants are considered, the value of 3.5 mPts/MJ can be used. In order to take into account formed pollutants, the value of b_{fuel} equal to 5.38 mPts/MJ is used. This value includes the environmental impact of pollutant formation.

It is usually assumed that the component-related environmental impact (Y_k) is negligible in an exergoenvironmental analysis of energy conversion systems [9] [16]. Based on collected data and specified assumptions, the values of the environmental impact rate B_j and the specific (exergy-based) environmental impact b_j of all the streams are obtained by solving the system of Equations (34)-(48). The results are shown in **Table 6**. Equations (50)-(56) are used to estimate the exergoenvironmental parameters of the different components of the NGCC. **Table 7** summarizes the environmental impact difference (r_b) of each equipment of the power plant.

Table 6. Stream-level environmental impact rate.

	b_j (mPts/MJ)	E_j (MJ/s)	B_j (mPts/s)
b1	0.00	0.00	0.00
b2	8.08	147.51	1192.56
b3	8.08	126.68	1024.19
b4 (fuel)	3.50	1167.81	4087.33
bAK	6.85	-	1192.76
bccPF	5.45	336.12	1833.21
b5	37.35	136.86	5111.40
b6	5.56	979.29	5447.99
b7	8.08	20.83	168.37
b8	6.33	1026.05	6497.81
bGT	6.85	-	4850.38
bST	6.85	-	1463.84
bp	6.85	-	21.54
b9	6.33	260.20	1647.79
b10	7.02	13.81	96.93
b13	7.02	2.82	19.78
b18	7.99	109.83	877.92
bRK	6.85	-	861.82
b20	7.90	0.01	0.06

Continued

b21	7.90	2.74	21.66
b22	7.90	188.71	1490.97
b23	7.90	153.70	1214.37
b24	7.90	175.52	1386.76
b25	7.90	56.43	445.82
b26	7.90	81.16	641.23
b27	7.90	13.76	108.75
b30	7.02	3.89	27.31
b40	7.02	0.05	0.35

Table 7. Exergoenvironmental parameters.

Equipment	$b_{F,k}$ (mPts/MJ)	$b_{P,k}$ (mPts/MJ)	$B_{D,k}$ (mPts/s)	B_L (mPts/s)	B_k^{PF} (mPts/s)	$r_{b,k}$ (%)
Compressor (AK)	6.85	8.08	182.89	0.00	0.00	18.11
Combustor (CC)	**87.64**	**52.26**	**1895.37**	**0.00**	**1833.21**	**32.19**
Gas Turbine (GT)	1541.57	1773.94	635.00	0.00	0.00	8.10
Heat Recovery Steam Generator (HRSG)	1.20	1.22	377.62	0.00	0.00	5.96
Pump (P)	0.03	0.03	1.61	0.00	0.00	15.07
Compressor (RK)	3.50	3.69	48.51	0.00	0.00	20.74
Steam Turbine (ST)	5.88	6.85	125.95	0.00	0.00	10.03
NGCC	3.50	1846.07	1598.18	27.67	1833.21	73.39

The final stage of this investigation is to evaluate the environmental impact of electricity (EIE) of the Natural Gas Combined Cycle (NGCC) power generation plant. Based on Equations (57) and (58), the values are respectively 34.26 mPts/kWh (exergy destruction only) and 34.42 mPts/kWh (including exergy loss).

4. Analysis of Results and Discussion

Based on the results shown in Table 5, the combustor (CC) is the main contributor to the exergy destruction of the power plant. The values of its exergy destruction ratio (y_D) and its exergy efficiency are respectively 24.35% and 75.65%. The Heat Recovery Steam Generator (HRSG) has the lowest contribution to the exergy destruction of the power plant with the values of its exergy destruction ratio (y_D) and its exergy efficiency respectively equal to 5.63% and 94.37%. This last result could be explained by the fact that the HRSG was simulated without heat loss. The overall exergy efficiency of the NGCC power plant is equal to 53.28%. Based on the results of the first study [14], the energy efficiency of the NGCC power plant (based on the low heating value (LHV) of the natural gas) is 58.2%.

In concordance with the exergetic analysis, the results of the exergoenvironmental analysis (Table 7), show that the combustor also presents the highest environmental impact of exergy destruction. Moreover, the combustor also has the highest contribution to the total environmental impact of the final product (r_b = 32.19%). In agreement with the exergetic analysis, the HRSG has also the lowest environmental impact of exergy destruction and the lowest contribution to the total environmental impact of the final product (r_b = 5.96%).

The environmental impact of a kWh of electricity of the power plant was 34.26 mPts/kWh (exergy destruction only), and 34.42 mPts/kWh (both exergy destruction and exergy loss). It should be noted that Açıkkalp *et al.* [12] estimated the environmental impact per kWh of produced electricity of a combined cycle power plant producing 80 MW to be 30.5 mPts/kWh at the same operating conditions. In order to decrease the environmental impact of the power plant, it is recommended to focus mainly on the components of the plant which have the highest environmental impact. The following steps are suggested: 1) the recoverable performance loss in the equipment can be easily rectified by water washing or, more thoroughly, by mechanically cleaning the combustion chamber and the two compressors. 2) The non-recoverable loss of performance caused by reduction in component efficiencies, could be corrected by replacement of affected parts during inspection intervals. 3) Since the furnace has the highest environmental impact, it is also recommended a process control system for continuous measurement of exhausted O_2 and CO in order to help reduce the amount of combustible and the excess air. This may also decrease the power required by the two compressors. Because a number of factors including auto-ignition, flame temperature, emissions and stability depend on fuel specifications, it is also recommended to check if the fuel composition meets the original equipment manufacturer (OEM) specification.

5. Conclusion

The main objective of this study was to evaluate the performance of an NGCC power plant by calculating its efficiency and evaluate its environmental impact using exergy based analyses. For the overall power plant, the exergy efficiency was equal to 53.28%. The environmental impact of a kWh of electricity of the power plant was 34.26 mPts/kWh (exergy destruction only), and 34.42 mPts/kWh (both exergy destruction and exergy loss). It was found that the combustor is the main source of exergy destruction in the power plant and has the highest contribution to the environmental impact. The analyses were followed by recommendations on how to enhance the exergetic efficiency of the power plant and, in this way, decrease its environmental impact.

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Nomenclature

AK: air compressor

B_j: environmental impact rate of the *j*-th material stream (Eco-indicator 99) (mPts/s)

b_j: specific environmental impact rate of the *j*-th material stream (Eco-indicator 99) (mPts/MJ)

CC: combustor

CCS: carbon capture and storage

E: exergy rate (MW)

ED: exergy destruction (MW)

EE: exergetic efficiency

EIE: environmental impact of electricity produced (mPts/kWh)

EL: exergy loss (MW)

e: specific exergy (kJ/kg)

f_b: exergoenvironmental factor, which expresses the relative contribution of component-related environmental impact to the sum of environmental impacts associated with the component (%)

h: specific enthalpy (kJ/kg)

HHV: high heating value (MJ/kg)

HP: high pressure

IP: intermediate pressure

LHV: low heating value (MJ/kg)

LP: low pressure

m: mass flow rate (kg/s)

NGCC: natural gas combined cycle

GT: gas turbine

OCGT: open cycle gas turbine

Q: heat rate (MW)

r_b: relative difference of exergy-related environmental impacts (dimensionless)

RK: compressor for recirculated flue gas

s: specific entropy (kJ/kg.K)

ST: steam turbine

W: work rate (MW)

Y: component-related environmental impact rate associated with the life cycle of the component (Eco-indicator 99) (mPts/s)

y: exergy destruction ratio, which compares the exergy destruction within component with the exergy destruction within the overall system (%)

Subscripts

CC: combustor

Ch: chemical

CV: control volume

D: destruction

F: fuel

fg: fuel gas
i: chemical species
j: *j*-th stream
K: compressor
k: *k*-th component of the plant
L: lost
P: product
Ph: chemical
Q: heat
T: total
TB: turbine
W: work
0: dead state
Superscripts
i: chemical species
PF: pollutants formation