Effect of Summer Weather Conditions on the Environmental Impact of a Power Plant in the UAE

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Abstract-**This work investigates the effect of summer weather conditions on the environmental impact of an Open Cycle Gas Turbine in Abu Dhabi (UAE) using an exergoenvironmental analysis. The results are used to suggest measures for reducing the calculated impact. Actual operational data are verified with simulation data using commercial software. Compared to standard weather conditions, the summer weather conditions decrease the overall exergetic efficiency of the plant by 4.3% and increase the total environmental impact per generated KWh by 7.9%. The addition of a heat recovery steam generator could increase the net power output and decrease the total environmental impact of the plant. The main contributor to the environmental impact of exergy destruction is the combustor. Summer conditions increase this impact by 21.5%. The compressor has the second highest environmental impact, increased by 14.6% for summer conditions. A process control system for continuous measurement of exhausted O2 and CO can help to reduce the excess air and, consequently, the associated environmental impact. This may also decrease the power required by the compressor. Lastly, a cooling system for the ambient air may also help to increase the power output of the plant by decreasing the power required by the compressor.**

Keywords- Open Cycle Gas Turbine; Exergetic Analysis; Exergetice Efficiency; Exergoenvironmental Analysis; Summer Weather Conditions

NOMENCLATURE

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)

E   exergy rate (MW)

ED   exergy destruction (MW)

EE   exergetic efficiency

EIE   environmental Impact of Electricity produced   (mPts/kWh)

EL   exergy loss

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)

LHV   low heating value (MJ/kg)

 m   mass flow rate (kg/s)

OCGT   Open Cycle Gas Turbine

Q   heat rate (MW)

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

s   specific entropy (kJ/kg.K)

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

I.   INTRODUCTION

Power generation plants play a decisive role in the economic growth of the UAE. However, these facilities contribute greatly to the annual CO2 emissions of the country. In 2013, power plants were responsible for about 33% of the 200 Million tons of the total CO2 emitted in the country [1]. The standard weather conditions used for the design of the gas turbines are 288 K, sea level atmospheric pressure and 60% relative humidity [2]. Thus, CO2 emissions from power generation plants increase during the summer months because of the negative effect of higher ambient temperatures on their performance. This is linked to the simple fact that the net power output of a plant will decrease because the compressor will require more power to compress air at a higher temperature.

Rahman et al. [3] studied the effects of the temperature of ambient air on the performance of a gas turbine in Malaysia. Their results showed that its energy efficiency and power output decreased linearly with the increase of the ambient temperature. Kakaras [5] reported that the gas turbine output and efficiency is strongly related to the ambient air temperature. Depending on the gas turbine type, the ISO-rated power output is reduced by a percentage between 5 and 10 percent for every 10 K increase in ambient air temperature. At the same time, the specific heat consumption increases by a percentage between 1.5 and 4. Altayib [4] conducted an exergetic analysis of a power plant in Makkah (KSA) consisting of 18 gas turbine units. Based on his investigation, the energetic and exergetic efficiencies of the plant increased by 20% and 12%, respectively, when the compressor inlet temperature was cooled down by 10 K. Okechukwu and Imuentinyan [6] conducted an exergetic analysis of a 335 MW natural gas-based gas turbine power plant in Nigeria. The obtained data showed that the combustion chamber had the largest exergy destruction percentage, equal to 54.15%. The effect of ambient temperature variations between 294 K and 306 K were also investigated. The authors recommended that a cooling system should be installed in order to decrease the effects of the high temperature of ambient air on the performance of the plant. The effect of ambient temperatures lower than the standard temperature (288 K) on the performance of power plants has also been studied. Açıkkalp et al. [7, 21] studied this

effect of increasing ambient temperature from 273 K to 298 K on the exergetic efficiency, the exergy destruction rate and the exergy destruction ratio of an electricity-generating facility in Turkey. The natural gas plant generated 37 MW in the gas turbine and 18 MW of in the steam turbine. Their results indicate that the overall exergetic efficiency of the power plant decreased by 7.9%, from 82% to 75.5%, as the ambient temperature increased from 273 K to 298 K. When looking at the individual components, the effect of ambient temperature increase was stronger on the combustor chamber and the air compressor, where the exergy destruction ratios were increased by 27 % and 19%, respectively, for the mentioned temperature increase. On the other hand, the change in ambient temperature had no effects on the exergetic efficiency of the expander of the gas turbine system.

The effects of ambient temperature on the environmental impact of the plant must also be accounted for, in order to ensure sustainable operation. To achieve this, the environmental impact of each plant component must be compared to its corresponding impact under standard conditions. Several approaches that study the environmental impact of industrial processes by combining exergetic analysis with environmental assessments are presented in literature [8-13]. For example, Szargut proposed the cumulative exergy consumption (CExC) as an environmental indicator [8]. The proposed exergoecological analysis [9, 10] and extended exergy accounting [11, 12] also use the CExC, while they also account for additional aspects. Another example for the combination of exergetic and environmental analysis is the environomic method, which is an extension of an exergoeconomic approach considering environmental aspects by internalizing external costs caused by pollutants [13]. This work uses the exergoenvironmental analysis [14-20] in order to evaluate the environmental impact of the analyzed power plant. The exergoenvironmental analysis of an energy conversion system is realized 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 [14]. The analysis involves the calculation of useful exergoenvironmental variables used in the overall environmental evaluation of the energy conversion system [14].

Morosuk et al. [15] analyzed a cogeneration plant based on an open-cycle gas-turbine power system using exergoenvoronmental analysis with five different indicators (ECO-95, ECO-99, CExC, CML and ECO-F2006). The authors concluded that the environmental impact of many energy conversion systems could be improved simply by improving their thermodynamic efficiency. Petrakopoulou et al. [19] also studied the environmental impact of a three-pressure level combined cycle power plant. The estimated value of the environmental impact of electricity (14.69 mPts/kWh) was found to be much lower than the average value 27 mPts/kWh for power plants in Europe [14]. When including the formation of pollutants in the calculations, the value increased to 25.1 mPts/kWh [20]. Petrakopoulou et al. [18] also used an exergoenvironmental analysis to compare the total environmental impact of an oxy-fuel combined cycle power plant with chemical looping combustion (CLC) for approximately 100% CO2 capture to a reference power plant without emission control. Their results indicate that adding CLC decreased the environmental impact associated with exergy destruction of the combustion by 12%. In addition, the total environmental impact of the plant decreased by 28.1 % (. Açıkkalp et al. [21] found that the environmental impact per kWh of produced electricity of a combined cycle power plant was 30.5 mPts/kWh at 284 K. The effect of ambient temperatures lower than the standard conditions (288 K) was found to be significant for the environmental impact of the combustor, which increased from 167mPts/s to 223 mPts/s for an ambient temperature change from 273 K to 298 K.

In a previous investigation, an exergetic analysis was conducted in order to locate and evaluate the exergy destruction within the plant during summer weather conditions. The software Aspen Hysys V8.6 with the Soave-Redlich-Kwong (SRK) equation was used to simulate the power plant using standard weather conditions [22]. The main goal of this second part of the study is to conduct an exergoenvironmental analysis of the power plant, in order to study the effects of ambient temperature on the environmental impact of the electricity produced by the plant and for each component of the power plant. The environmental impact assessment is realized using the life cycle impact assessment (LCIA) method Eco-indicator 99.

II. METHODS

A. Exergetic Analysis

Unlike energy, exergy is not conserved in any real process. As a consequence, an exergy balance must contain a "destruction" term, which may be eliminated only for a reversible process. The general form of an exergy balance of a control volume can be written as [23]

$$\frac{dE_{CV}}{dt} = \Sigma E_{heat} + E_{work} + \Sigma m_{in} \cdot e_{T,in} - \Sigma m_{out} \cdot e_{T,out} - ED \tag{1}$$

For a steady state system, Equation (1) can be rewritten as [23]:

$$0 = \Sigma E_{heat} - W_{cv} + \Sigma m_{in} \cdot e_{T,in} - \Sigma m_{out} \cdot e_{T,out} - ED \tag{2}$$

The total specific exergy transfer at the inlet and outlet can be written as [23]:

$$e_T = (h - h_0) - T_0 (s - s_0) + \sum x_i \cdot e_{Ch}^i + R.T. \sum x_i \cdot \ln x_i \tag{3}$$

where, h and s are the specific enthalpy and entropy of the streams and h0 and s0 are the specific enthalpy and entropy of the restricted dead state (atmosphere). An exergetic analysis quantifies the magnitude and identifies the source of thermodynamic

inefficiencies in a power plant. The exergy destruction (E) within a plant component is the measure of irreversibility that is the source of performance deficiency.
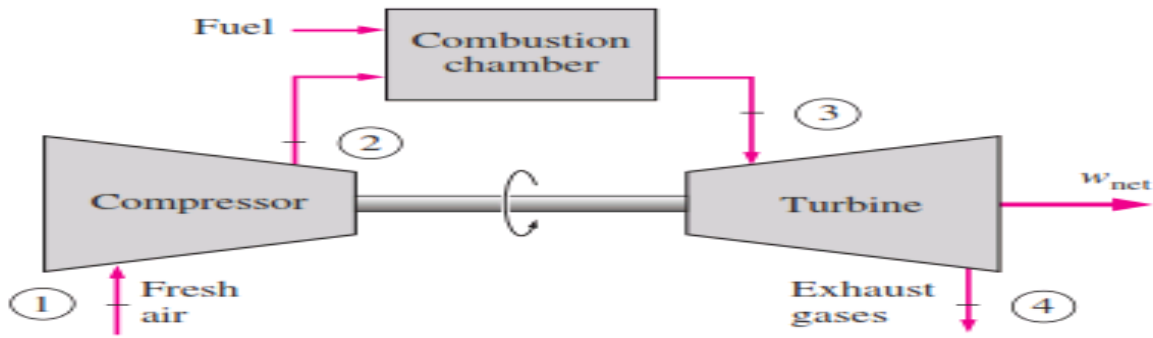

Fig. 1 Schematic Diagram of an Open Cycle Gas Turbine [3]

Based on Fig. 1, the exergy destruction (ED) and exergetic efficiency (EE) for the three main components of an open cycle gas turbine (OCGT) are defined using the following equations [23]:

Compressor (K)

$$(ED)_K = W_K - m_{air} \, (e_{T2} - e_{T1}) \tag{4}$$

$$(EE)_K = 1 - \frac{(ED)_K}{W_K} \tag{5}$$

where, W_K is the work required by the compressor and e_T the specific exergy of its outlet and inlet streams.

Combustor (CC)

$$(ED)_{cc} = m_{air} \cdot e_{T2} + m_{fuel} \cdot e_{fuel} - m_{fg} \cdot e_{T3}$$

$$(EE)_{cc} = 1 - \frac{(ED)_{cc}}{m_{air} \cdot e_{T2} + m_{fuel} \cdot e_{fuel}} \tag{6}$$

where, m_{fg} is the flow rate of the flue gas exiting the combustor.

Turbine (TB)

$$(ED)_{TB} = m_{fg} \cdot (e_{T3} - e_{T4}) - W_{TB} \tag{7}$$

$$(EE)_{TB} = 1 - \frac{(ED)_{TB}}{m_{fg} \cdot (e_{T3} - e_{T4})} \tag{8}$$

where, W_{TB} is the work produced by the expander of the gas turbine system,

$$W_{TB} = W_{NET-OUT} + W_K \tag{9}$$

and $W_{NET-OUT}$ is the net work produced by the gas turbine.

The exergy of the exhaust gas leaving the turbine (Stream 4) constitutes the exergy loss ($EL = m_{fg} \cdot e_{T4}$) of the power plant.

The rate of the exergy of the product of the k-th component ($\widehat{E}_{P,k}$) is the exergy of the desired output resulting from the operation of the component, while the rate of the exergy of the fuel of the same component ($\widehat{E}_{F,k}$) is the expense in exergetic resources for the generation of the desired product. The rate of the exergy of the fuel and product of the three main components and the studied power plant are presented in Table 1 [23].

TABLE 1 DEFINITIONS OF THE EXERGY OF THE FUEL AND PRODUCT FOR EACH COMPONENT

Equipment	$\widehat{E}_{F,k}$ (MW)	$\widehat{E}_{P,k}$ (MW)
Compressor	W_K	$m_{air} \, (ex_{T2} - ex_{T1})$
Combustor	$m_{air} \cdot e_{T2} + m_{fuel} \cdot e_{fuel}$	$m_{fg} \cdot e_{T3}$
Turbine	$m_{fg} \cdot (e_{T3} - e_{T4})$	$W_{NET-OUT} + W_K$
OCGT	$m_{fuel} \cdot e_{fuel}$	$W_{NET-OUT}$

The exergy balance and exergetic efficiency of the overall power plant are [23]:

$$\hat{E}_{F,total} = \hat{E}_{P,total} + \widehat{ED}_{total} + \hat{E}_{L,total} \tag{10}$$

$$(EE)_{total} = 1 - \frac{\widehat{ED}_{total} + \hat{E}_{L,total}}{\hat{E}_{F,total}} \tag{11}$$

The rate of exergy destruction within the kth component, $(ED)_k$, is calculated as the difference between its rate of fuel and product exergy [23]:

$$(ED)_k = \hat{E}_{F,k} - \hat{E}_{P,k} \tag{12}$$

Lastly, a useful variable calculated in the exergetic analysis is the exergy destruction ratio (yD) that shows which percentage of the total exergy of the fuel provided to the overall plant is destroyed within each one of the individual components. It is defined as [23]:

$$y_{D,k} = 100 \frac{(ED)_k}{\hat{E}_{F,k}} \tag{13}$$

B. Exergoenvironmental Analysis

An exergoenvironmental analysis reveals the relative importance of each plant component constituting an energy system, with respect to environmental impact. It also offers options for reducing the environmental impact of the plant. In an exergoenvironmental analysis, a one-dimensional characterization indicator is obtained using a Life Cycle Assessment (LCA). LCA is a methodology 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 [24]:

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

Proxy measures use a single value to represent the environmental impact of a product or material. An example of proxy measures is the life cycle impact assessment (LCIA) method Eco-indicator. The Eco-indicator of a material or a process is a number that indicates its overall environmental impact. The higher the indicator is, the greater the environmental impact of the process. LCIA methods, like Eco-indicator 95 [12], Eco-indicator 99 [14] and the Swiss Ecoscarcity [17] have been successfully utilized for energy conversion systems.
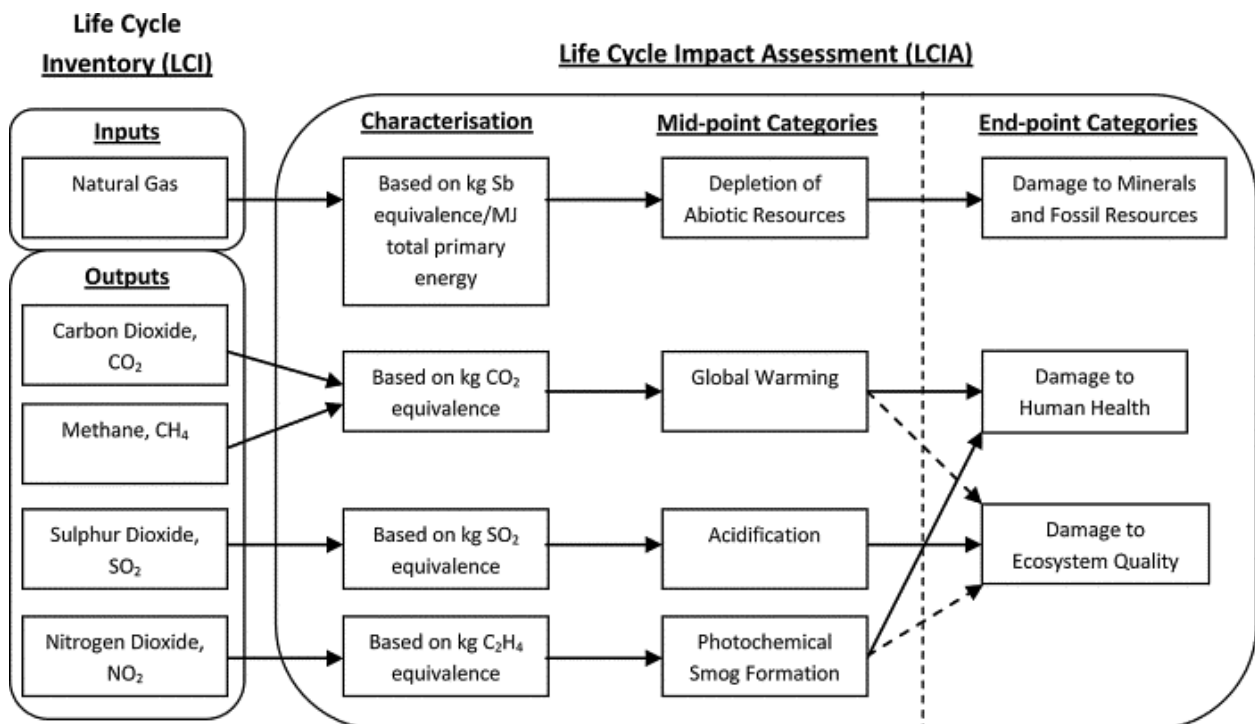

Fig. 2 Typical LCA framework linking the LCI to end-point categories for selected damage types via mid-point categories [25]

Eco-indicator 99 has been evaluated by various authors [26-29], with respect to its suitability in LCA-related issues and several LCA software packages support it (e.g., SimaPro and Gabi) [23]. As also seen in Fig. 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 LCIA converts these flows into simpler indicators.

The environmental impact rate Bj of the j-th material stream is calculated using its specific exergy exj, mass flow rate mj and specific environmental impact bk [16]:

$$B_j = E_j . b_j = m_j . e_j . b_j \qquad (14)$$

Bj is expressed in Eco-indicator points per unit of time (Pts/s or mPts/s). The specific (exergy-based) environmental impact bj is the average environmental impact associated with the production of the stream per unit of exergy of the same stream [Pts/(GJ exergy), i.e., mPts /(GJ exergy)] [7]. Using the physical and chemical components of the specific exergy, the environmental impact rate Bj can be written as [16]:

$$B_j = m_j . e_{Ph} . b_{Ph} + m_j . e_{Ch} . b_{Ch} = m_j . b_j \qquad (15)$$

The environmental impact rates associated with heat Q and work W streams are calculated as [16]:

$$B_Q = b_Q . E_Q \qquad (16)$$

$$B_W = b_W . E_W \qquad (17)$$

The exergy rate associated with heat transfer is calculated using the following equation [16]:

$$E_Q = \left(1 - \frac{T_0}{T_k}\right). Q \qquad (18)$$

where, T0 is the ambient temperature and Tk 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 of all streams exiting each individual process, $B_{j,out}$. Thus, similar to an exergoeconomic analysis, the exergoenvironmental analysis is performed with a system of equations defined at the component level. 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 exiting streams [16]:

$$\Sigma_{j=1}^{n} B_{j,k}^{in} + Y_k = \Sigma_{j=1}^{m} B_{j,k}^{out} \qquad (19)$$

The component-related environmental impact of the k-th component of the plant (Yk) includes the three life-cycle phases of construction (YCO,k) (manufacturing, transport and installation), operation and maintenance (YOM,k) and disposal (YDI,k) [16]:

$$Y_k = Y_{CO,k} + Y_{OM,k} + Y_{DI,k} \qquad (20)$$

Using data from the exergetic analysis and the LCA, the specific environmental impact bk is calculated as:

$$b_{k,in} = \frac{B_{k,in}}{E_{k,in}} \qquad (21)$$

The equations of each component used in the exergoenvironmental analysis are shown in Table 2 [16].

TABLE 2 ENVIRONMENTAL IMPACT BALANCES

Equipment	Environmental impact balance	Auxiliary equations
Compressor	$b_2 . E_2 = b_1 . E_1 + b_K . W_K + Y_K$	$b_1 = 0$ (fresh air)
Combustor	$b_3 . E_3 = b_2 . E_2 + b_{fuel} . E_{fuel} + (Y_{CC} + B_{CC}^{PF})$	b_{fuel} and b_{CO2}^{PF} [20]
Turbine	$b_4 . E_4 + b_{TB} . W_{TB} = b_3 . E_3 + Y_T$	$b_4 = b_3$ $b_K = b_{TB}$

The environmental impact balance of each component includes its environmental impact of product and fuel, $B_{P,k}$ and $B_{F,k}$. The environmental impact of exergy destruction in the power generation plant has been calculated by multiplying the exergy destruction with the specific environmental impact of the fuel of the plant. The environmental impact rate of fuel and product for the three components of the plant are shown in Table 3 [16].

TABLE 3 DEFINITIONS OF ENVIRONMENTAL IMPACT OF FUEL AND PRODUCT FOR THE PLANT COMPONENTS

Equipment	Environmental impact rate of fuel $B_{F,k}$ (mPts/s)	Environmental impact of product $B_{P,k}$ (mPts/s)
Compressor	$b_K . W_K$	$b_2 . E_2 - b_1 . E_1$
Combustor	$b_2 . E_2 + b_{fuel} . E_{fuel} + B_{CC}^{PF}$	$b_3 . E_3$
Turbine	$b_3 . E_3 - b_4 . E_4$	$b_{TB} . W_{TB}$
OCGT	$\mathbf{b_{F,OCGT} . m_{fuel} . e_{fuel}}$	$\mathbf{b_{P,OCGT} . W_{NET-OUT}}$

The total environmental impact associated with component k includes the environmental impact of exergy destruction $B_{D,k}$ and the component-related environmental impact Yk. 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 and it accounts for the amount of pollutants formed, such as CO, CO2, CH4, NOx and SOx [16].

$$B_{P,k} = B_{F,k} + Y_k + B_k^{PF} \tag{22}$$

Here, the pollutant formation is determined by the formed CO2 emissions [16]:

$$B_{CC}^{PF} = b_{CO2}^{PF} \cdot (m_{CO2,out} - m_{CO2,in}) \tag{23}$$

The average specific (exergy-based) environmental impacts of product and fuel for the kth component are [16]:

$$b_{P,k} = \frac{B_{P,k}}{\hat{E}_{P,k}} \tag{24}$$

and

$$b_{F,k} = \frac{B_{F,k}}{\hat{E}_{F,k}} \tag{25}$$

As commonly realized, the environmental impact of exergy destruction of each plant component is calculated by multiplying its exergy destruction with the specific environmental impact of the fuel. Thus, the environmental impact rate of fuel of the k-th component ($B_{D,k}$) is defined as [16]:

$$B_{D,k} = b_{F,k} \cdot ED_k \tag{26}$$

The environmental impact of electricity (EIE) of the OCGT is estimated using the environmental impact balance applied to the overall system [16]:

$$EIE = \frac{(b_{F,tot}\dot{E}_{F,tot} + \dot{Y}_{tot} + \dot{B}_{tot}^{PF})}{\hat{E}_{P,tot}} \tag{27}$$

When the environmental impact associated with the exergy losses of the overall system is charged to the product, we obtain [16]:

$$EIE_T = \frac{(b_{F,tot}\dot{E}_{F,tot} + \dot{Y}_{tot} + B_{tot}^{PF} + B_{L,tot})}{\hat{E}_{P,tot}} \tag{28}$$

The exergoenvironmental analysis does not only identify the components with the highest environmental impact, but it also reveals the possibilities and trends for improvement, in order to decrease the environmental impact of the overall plant. These trends can be identified using the relative environmental impact difference (rb,k) and the exergoenvironmental factor (fb,k) [16]. The environmental impact difference (rb,k) of the k-th component of the power plant depends on the environmental impact of its exergy destruction (BD,k) and its component-related environmental impact (Yk) [16]:

$$r_{b,k} = \frac{1 - EE}{EE} + \frac{Y_{k + B_k^{PF}}}{B_{D,k}} = \frac{b_{P.k} - b_{F,k}}{b_{F,k}} \tag{29}$$

rb,k is an indicator of the reduction potential of the environmental impact associated with the component. In general, a relatively high value of rb,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. Independent of the absolute value of the environmental impacts, the relative difference of specific environmental impacts represents the environmental quality of a component.

The sources of environmental impact formation in a component are compared using the exergoenvironmental factor fb,k that shows the relative contribution of the component-related environmental impact Yk to the sum of its environmental impacts [16]:

$$f_{b,k} = \frac{Y_k}{Y_k + B_{D,k} + B_k^{PF}} \tag{30}$$

In the majority of the energy conversion systems, the value of $f_{b,k}$ has been shown to be negligible [8].

III. OPERATION OF THE POWER PLANT

The power plant under investigation is an open cycle gas turbine designed to produce 165 MW. As shown in Fig. 1, the OCGT is divided into three different sections (Compression, Combustion and Expansion). The compressor is an axial compressor with 21 stages and a compression pressure ratio of 13.5. The combustion chamber is equipped with 72 environmental burners. The average temperature and pressure of the fuel gas are 303 K and 2510 kPa, respectively. The expansion section is composed of a 5-stage gas turbine and a generator. The average temperature of the exhaust gas exiting the turbine (Stream 4) is 886 K and the deduced turbine isentropic efficiency is 88%.

IV. POWER PLANT EVALUATION

A. Exergetic Analysis

The results of the investigation on the exergetic analysis of the power plant are summarized in Tables 4-6 [22]. The average values of the summer operating conditions and the specific total exergy of each stream (Fig. 1) are shown in Table 4.

TABLE 4 STREAM-LEVEL RESULTS [22]

Streams	T (K)	P (kPa)	Flow (kg/s)	h (kJ/kg)	s (kJ/ kg.K)	e_T (kJ/kg)
1 (ambient air)	316.00	100.80	484.0	-352.20	5.49	0 (dead state)
2 (compressed air)	714.20	1361.00	484.0	79.10	5.61	394.30
Fuel (natural gas)	303.00	2510.00	9.6	-4053.36	8.94	48642.50
3 (flue gas)	1480.00	493.60	493.6	-233.13	6.92	1133.80
4(exhaust gas)	886.00	100.80	493.6	-1003.00	7.04	337.44

The values of the exergy destruction and the exergy efficiency of each component of the power plant are obtained by solving the system of equations 6-13. The results are shown in Table 5.

TABLE 5 COMPONENT-LEVEL EXERGY RESULTS [22]

Equipment k	$\hat{E}_{D,k}$ (MW)	$\hat{E}_{D,k}$ (%)	$\hat{E}_{F,k}$ (MW)	$\hat{E}_{P,k}$ (MW)	$y_{D,k}$	EE_k (%)
Compressor	17.44	13.55	208.80	190.84	3.73	91.60
Combustor	98.15	76.28	657.81	559.64	21.0	85.10
Turbine	13.08	10.17	393.08	380.0	2.80	96.60
OCGT	**128.67**	**100.00**	**466.97**	**160.40**	**26.53**	**33.10**

The previous input data and obtained results are here verified through the simulation of the power plant using the software Aspen Hysys V8.6 with the Soave-Redlich-Kwong (SRK) equation of state. The simulation of the process is realized under the same operating and weather conditions (T=288 K, absolute humidity of 0.008 kg.m-3). The results of the exergetic analysis and the values of the exergy of the fuel and product for each plant component are shown in Table 6.

TABLE 6 COMPONENT-LEVEL EXERGY RESULTS AT STANDARD CONDITIONS (BASED ON SIMULATION)

Equipment k	$\hat{E}_{D,k}$ (MW)	$\hat{E}_{D,k}$ (%)	$\hat{E}_{F,k}$ (MW)	$\hat{E}_{P,k}$ (MW)	$y_{D,k}$	EE_k (%)
Compressor	14.94	11.90	183.80	166.35	3.20	92.00
Combustor	80.92	64.70	633.30	551.10	17.33	87.40
Turbine	29.12	23.30	391.92	362.8	6.24	92.60
OCGT	**125.0**	**100.00**	**466.97**	**168.6**	**26.77**	**34.60**

According to results obtained using Hysys V8.6, the power generated by the turbine and the power needed by the compressor for summer conditions are 380 MW and 208.8 MW, respectively. Assuming a mechanical efficiency for the turbine and compressor equal to 98% and a generator efficiency equal to 98%, the power plant generates 160.4 MW net under summer conditions. The net output of the operating power plant under standard conditions is 165 MW while our simulation indicates that the net power produced at design conditions is 168.6 MW. The relative shift of 2.2% presents an acceptable margin of error. Fig. 3 shows the effects of summer weather conditions on the exergy destruction ratio (yD) of each component of the power plant.
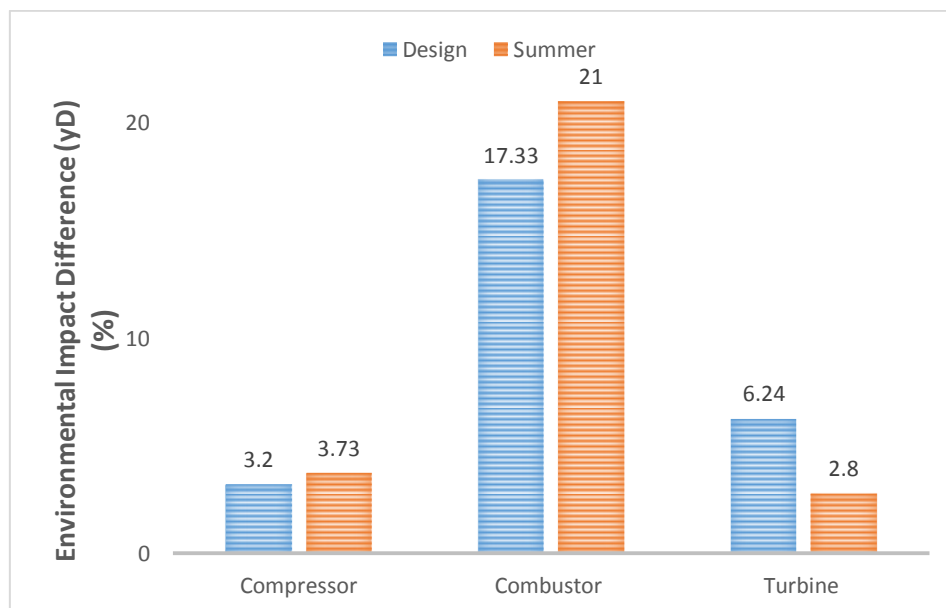
Fig. 3 Effects of summer weather conditions on exergy destruction ratio (yD)

B. *Exergoenvironmental Analysis*

The specific environmental impact of carbon dioxide and the depletion of fuel in Eco-99 points were selected from literature [15]. As shown in Fig. 2, three end-point categories of the LCIA are considered: Damage to human health, damage to ecosystem quality and damage to fossil resources.

Global warming (kg(CO2-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 [15].

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 bfuel equal to 5.38 mPts/MJ is used. This value includes the environmental impact of pollutant formation [15].

It has been shown that the component‑related environmental impact (Yk) is negligible in an exergoenvironmental analysis [15-16]. Thus, it has not been considered here. Based on collected data and specified assumptions, the values of the environmental impact rate Bj and the specific (exergy-based) environmental impact bj of all the streams are obtained by solving the system of Equations. The results are shown in Table 7.

TABLE 7 STREAM-LEVEL ENVIRONMENTAL IMPACT RATE

Stream	Summer conditions		Standard conditions	
	b_j (mPts/MJ)	B_j (mPts/s)	b_j (mPts/MJ)	B_j (mPts/s)
WK	5.32	1110.60	5.42	992.50
WT	5.32	2021.60	5.42	1959.10
1	0	0	0	0
2	5.82	1110.60	5.97	993.10
Fuel	3.50	1634.40	3.50	1634.40
3	5.14	2879.00	5.01	2761.00
4	5.14	856.10	5.01	797.50

Equations (22)-(28) are used to estimate the exergoenvironmental parameters of the different components of the OCGT both at design and summer conditions (Tables 8 and 9). Fig. 4 summarizes the effects of summer weather conditions on the environmental impact difference (rb,k) of each equipment of the power plant.

TABLE 8 EXERGOENVIRONMENTAL PARAMETERS FOR SUMMER CONDITIONS

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)	$B_{D,k} + B_k^{PF} + B_L$ (mPts/s)	$r_{b,k}$ (%)
Compressor	5.32	5.82	92.78	0	0	92.78	9.4
Combustor	4.38	5.14	429.90	0	133.97	563.27	17.4
Turbine	5.14	5.32	67.36	0	0	67.36	3.5
OCGT	**3.50**	**16.40**	**450.34**	**856.10**	**133.97**	**1440.40**	**367.00**

TABLE 9 EXERGOENVIRONMENTAL PARAMETERS FOR STANDARD CONDITIONS

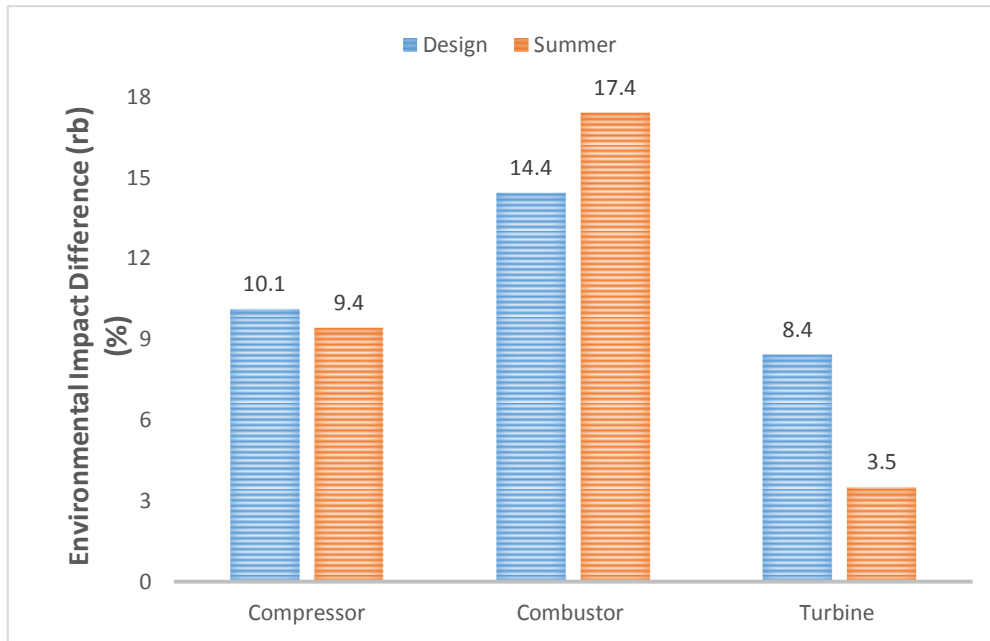| Equipment	$b_{F,k}$ (mPts/MJ)	$b_{P,k}$ (mPts/MJ)	$B_{D,k}$ (mPts/s)	B_L (mPts/s)	B_k^{PF} (mPts/s)	$B_{D,k} + B_k^{PF} + B_L$ (mPts/s)	$r_{b,k}$ (%)
Compressor	5.42	5.97	80.97	0	0	80.97	10.1
Combustor	4.37	5.00	353.60	0	133.97	487.60	14.4
Turbine	5.00	5.42	145.60	0	0	145.60	8.4
OCGT	**3.50**	**15.20**	**437.50**	**818.00**	**133.97**	**1389.50**	**335.00**

Fig. 4 Effects of summer weather conditions on Environmental Impact Difference (rb)

Based on Equations (27) and (28), the environmental impact of a kWh of electricity during summer weather conditions is 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. Lastly, summer weather conditions increase the total environmental impact of the power plant by 6.6% (without exergy loss) and 7.9% (including exergy loss). The effects of summer conditions on the environmental impact of electricity produced by the power plant are shown in Fig. 5.
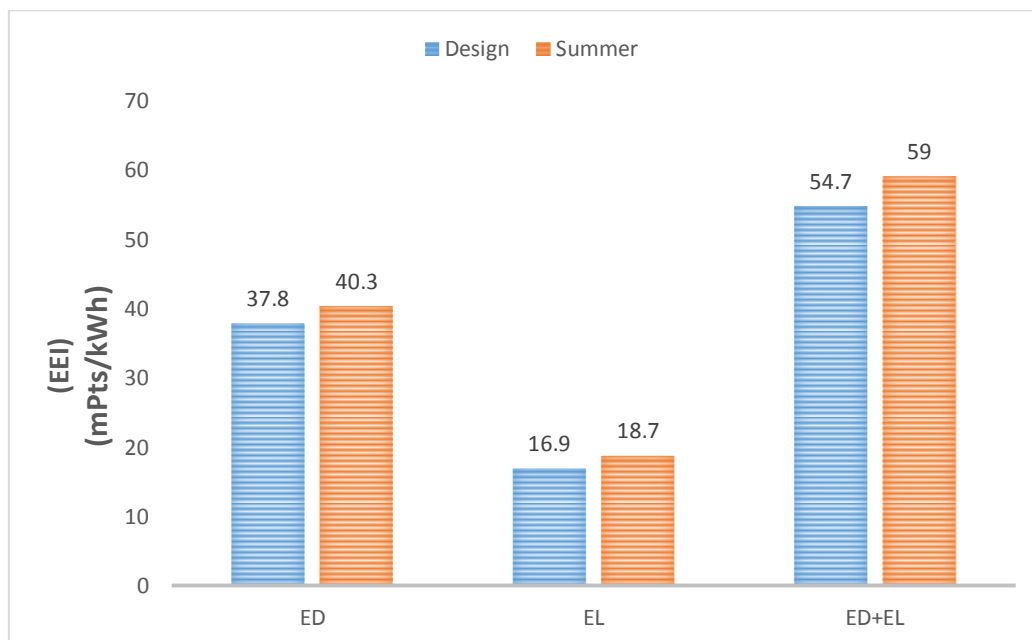

Fig. 5 Effects of summer weather conditions of environmental impact of electricity produced (ED: exergy destruction, EL: exergy loss)

V. RESULTS AND DISCUSSION

According to results shown in Tables 5 and 6, the combustor is the main contributor to the exergy destruction of the power plant. Summer conditions increase its exergy destruction ratio by 21.2 % from 17.3% to 21.0%, and decrease its exergetic efficiency by 2.6%, from 87.4 to 85.1%. The compressor is the second contributor to the exergy destruction of the power plant. The summer weather conditions increase its exergy destruction ratio by 16.5%, from 3.20% to 3.73% and slightly decrease (0.4%) its exergetic efficiency, from 92.0% to 91.6%. The turbine has the lowest contribution to the exergy destruction of the power plant. Due to important positive effects of higher temperatures at the entrance of the turbine, the summer weather conditions decrease its exergy destruction ratio by 55%, from 6.2% to 2.8% and increase its exergetic efficiency by 4.3%, from

92.6% to 96.6%. For the overall OCGT, summer weather conditions decrease its exergy destruction ratio by 0.9%, from 26.7% to 26.5% but decrease its exergetic efficiency by 4.3%, from 34.6% to 33.1% and its net power output by 4.9%, from 168.6 MW to 160.4 MW. The negative effects of summer weather conditions on the performance of the combustion chamber and the compressor are partly compensated by their positive effects on the performance of the turbine. In agreement with published work [7, 20], to the exergy destruction ratio of the combustor increase by 37%, from 11% to 15%, when the ambient temperature was increased from 273 K to 298 K. However, the exergetic efficiency of the combustor increased by 114%, from 28% to 60% when the temperature changed from 273 K to 298 K. This suggests that there is an optimum ambient temperature that maximizes the efficiency of the combustion process. The exergy destruction ratio of the compressor increased by 50%, from 2% to 3%, while its exergetic efficiency did not change significantly. According to Ref. [7], the effect of ambient temperature change is negligible for the other components of the plant including the expander of the gas turbine system. This could be linked to the fact that the ambient temperatures should be high enough for the corresponding temperatures of the flue gas to have positive effects on the performance of the turbine.

In agreement to the exergetic analysis, the results of the exergoenviromental analysis (Tables 8 and 9) indicate that the combustor also presents the highest environmental impact of exergy destruction. The summer weather conditions further increase this impact by 21.5%. In addition, the combustor also has the highest contribution to the total environmental impact of the final product (rb =14.4%), while summer weather conditions increase this contribution by 20.8%. The compressor has the second highest environmental impact of exergy destruction and summer weather conditions increase this impact by 14.6%. The compressor also has the second highest contribution to the total environmental impact of the final product (rb =10.1%). Unlike the combustor, the data indicate that summer weather conditions decrease this contribution by 7.4%. The expander has the lowest environmental impact of exergy destruction and summer weather conditions decrease this impact by 53.7%. The expander has the lowest contribution to the total environmental impact of the final product (rb =8.4%), while summer weather conditions decrease this contribution by 58.3%.

Fig. 5 indicates that the environmental impact of a kWh of electricity during summer weather conditions is increased by 6.6% (exergy destruction only), 10.7 % (exergy loss only) and 7.9% (for both exergy destruction and exergy loss). According to published work presenting the effects of low ambient temperatures in Turkey on the environmental impact of a power plant [20], the combustor was found to have the highest environmental impact of exergy destruction of 167 mPts/s. This impact increased by 33.3% when the temperature changed from 273 K to 298 K. The environmental impact of exergy destruction of the compressor increased by 25%, from 55.5 mPts/s to 69.4 mPts/s. However, the change of ambient temperature had no effects on the environmental impact of the exergy destruction of the turbine. Finally, the data related to the environmental impact (30 mPts/kWh) of a kWh of electricity produced by the combined cycle gas turbine at 284 K was lower than the value of the environmental impact of the electricity produced by the open cycle gas turbine studied here (37.5 mPts/kWh) at standard weather conditions (288 K) and without exergy loss. This shows the necessity for an additional heat recovery steam generator (HRSG) to generate more electricity and decrease the total environmental impact of the power plant.

VI. CONCLUSIONS

The main objective of this study was to investigate the effect of summer weather conditions on the environmental impact of an Open Cycle Gas Turbine in Abu Dhabi (UAE). The operation of the power plant was evaluated using exergetic and exergoenvironmental analyses. 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. It was found that summer weather conditions decreased the net power output of the power plant by 4.9% and its exergetic efficiency by 4.3%. Moreover, summer conditions increased the total environmental impact of a kWh of electricity (including exergy loss) by 7.9%. To improve the environmental operation of the plant, thermodynamic inefficiencies, associated with the exergy lost via the exhaust gases and the exergy destruction of the plant components, must be reduced. The significant exergy of the exhaust gases increased the total environmental impact of the power plant by 30.9%. Summer weather conditions enhanced this contribution by 2.6%. In order to take advantage of the high temperature of the exhaust gases (886 K), the addition of a heat recovery steam generator (HRSG) to generate steam is recommended. The generated steam can be further used in a Ranking cycle to produce additional electricity. The goal is to decrease the total environmental impact of the overall power plant through the increased electricity.

It was also seen that the combustor had the highest environmental impact of exergy destruction, while summer weather conditions increased this impact by 21.5%. It is suggested to invest in a process control system based on a continuous measurement of both O2 and CO leaving the combustor. This could provide the needed information for more effective combustion with lower environmental impact through the minimization of the excess air. Lastly, the compressor had the second highest environmental impact of exergy destruction and summer weather conditions increased this impact by 14.6%. Future work could involve a thermoeconomic optimization to reveal the best cooling system (e.g., fogging cooling) to decrease the negative effect of high ambient temperatures on the exergetic efficiency of the component.

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