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## Article

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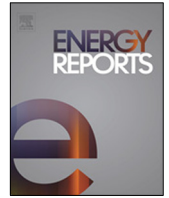
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## Research paper

# The effect of ambient temperature on electric power generation in natural gas combined cycle power plant—A case study



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## H I G H L I G H T S

- Performance analysis of CCGP has been carried out.
- The biggest effect for energy production is ambient temperature.
- 8 °C is ideal ambient temperature for generation.

## A R T I C L E I N F O

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## A B S T R A C T

Natural gas combined cycle power plants (CCPPs) are widely used to meet peak loads in electric energy production. Continuous monitoring of the output electrical power of CCPPs is a requirement for power performance. In this study, the role of ambient temperature change having the greatest effect on electric production is experimentally investigated for a natural gas CCPP. The plant has generated electricity for fourteen years and setup at 240 MW in Aliağa, İzmir, Turkey. Depending on the seasonal temperature changes, the study data were obtained from each gas turbine (GT), steam turbine (ST) and combined cycle blocks (CCBs) in the ambient temperature range of 8–23 °C. In electric energy production, an important decrease was in the GTs because of the temperature increase. This decrease indirectly affected the electric energy production of the STs. As a result, the efficiency of each GT, ST and CCB decreased, although the quantity of fuel consumed by the controllers in the plant was reduced. As a result of this data, it has been recommended and applied that additional precautions have been taken in the power plant to bring the air entering the combustion chamber to ideal conditions and necessary air cooling systems have been installed.

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## 1. Introduction

Energy founds in various forms such as heat, light, electricity, kinetic and potential in the environment. Today, energy is among the indispensables of mankind. Among the energy types, electricity energy is often used because it can be easily converted into other energy resources. The structures established for electricity generation are called power plants. These are hydropower, solar and solar

power plants. While fossil fuels such as petroleum, natural gas and coal are used for the production of electricity, recently renewable energy resources such as wind, sun and geothermal also are used.

Electric power generated by using fossil fuels is employed in conventional power plants. Thermal power and natural gas power plants are among these conventional power generation plants. These plants account for up to 80% of electricity energy production in the world (Abuelnuor et al., 2017). This amount is quite high (Kok and Benli, 2017). When energy expenditures and energy policies are considered in the world, it is not expected that this amount would fall in the future at a great rate. Since the unit production cost of renewable energy resources is still higher than the ones using traditional energy resources (Noroozian et al., 2017). Recent studies show that researches are conducted in that these plants are modernized and are made less harmful to the

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environment (Kotowicz and Brzeczek, 2018; Cihan et al., 2006; Incekara and Ogulata, 2017; Jović et al., 2018). Since these power plants are highly powerful, even a small improvement proves to achieve a power level of MWs (Blumberg et al., 2017).

Conventional electric energy production plants have some advantages. They have higher power generation, are installed close to energy resources, and are utilized to meet peak loads. Moreover, their technologies are more easily accessible (Ersayin and Ozgener, 2015). However, the fact that the gases emitted from these power plants cause damage to the environment and cause acid rain, also has the disadvantages such as throwing away the water used in the power plant without cleaning it (Zhang et al., 2017). But these disadvantages can be minimized by taking effective measures (Jović et al., 2018).

In conventional electric power generation plants, both gas turbines (GT) and steam turbines (ST) are used. There are also natural gas combined cycle power plants (CCPPs) that use these two types of turbines together (Mohanty and Venkatesh, 2014) and have recently received great attention due to their efficiency (Meegahapola, 2014). Brayton Cycle in GTs of CCPPs and Rankine Cycle in STs are used (Ahmadi and Toghraie, 2016; Xiang et al., 2018). Therefore, CCPPs provide lower environmental gas emissions, higher thermal efficiency and flexibility compared to other conventional power plants (Alobaid, 2018).

Monitoring of electric energy production is important for ensuring continuity of installed power efficiency since setup of a natural gas CCPPs (Pattanayak et al., 2017; Kaushik et al., 2011). Moreover, their thermodynamic modeling and continuous analysis of all hardware are an important measure to keep the yield value high (Promes et al., 2015; Ganjehkaviri et al., 2014; Javadi and Ghomashi, 2016). Considering all these facts, various studies have been carried out in the literature in order to increase the yields for natural gas CCPPs, to improve the working conditions of CCPP by performing energy and exergy analyzes and to minimize the harmful effects on environment.

Almutairi et al. (2015) had carried out an energetic and exergetic analyzes of a 2 GW CCPP operating at a yield of 54.5% on regional conditions. They argued that low-temperature heat source technologies would increase plant performance without additional fuel entry. Ameri et al. (2008) had conducted some analyzes of a CCPP of 420 MW. In the work, they fulfilled calculated the assessment of the irreversibility of each part of the Neka CCPP. Also, they showed that the fuel chamber, the GT, the channel burner and the heat recovery steam generator (HRSG) losses were 83% of all the energy losses. In addition to these, Tüfekci (2014) defined how the best CCPP installation is carried out based on six years of acquired CCPP data, in order to get the best performance by means of the machine learning regression method. In another study, Herraiz et al. (2018) had determined the exhaust gas recirculation in order to provide the best burning, to reduce the emission of flue gas and to increase the efficiency and to minimize the environmental damages in CCPPs. Moreover, Sahin et al. (2016) had performed an exergo-economic analysis of a CCPP and had reached different CCPP sizes and configurations in terms of energy-exergy efficiency, electricity cost and total investment criteria, for reducing electricity costs, minimizing environmental concerns and reducing investment costs. Ganjehkaviri et al. (2015) had suggested that the steam quality at the turbine outlet station should be kept at 88%, which was a more realistic and feasible value, for operating the ST in the CCPP at the optimum level. Ultimately, Kilani et al. (2017) had realized the comparison of CCPP in two different structures in which the vapor inlet in the fuel chamber was different. Firstly, the injected steam had been produced in the HRSG, while the other had been supplied using the HRSG placed at the outlet of the compressor. According to their results, the second project was more effective for increasing performance.

It is also important to predict the electricity supplied by the natural gas CCPPs to the network in order to meet the peak load (Lee et al., 2017). The output powers of the GTs used in these are the most effective parts of the system (Kim et al., 2017). For the reuse of unburned gas, processes are operated with additional devices in the CCPP system (Hu and Ahn, 2017). These output powers also vary with ambient temperature, pressure, relative humidity, fuel structure, heat and power drawn (Amell and Cadavid, 2002; De Sa and Al Zubaidy, 2011; Arrieta and Lora, 2005). From these variables, it was determined that the most effective one in the system is the ambient temperature depending on data records of fourteen years. Depending on this result, additional arrangements for the air cooler section have been added to the system to keep the air temperature entering the fuel chamber at about 8 °C. In this way, it is ensured to obtain the optimum level for the electricity production of used the energy source and operated the plant with the best efficiency.

In the first part of the present study, a brief introduction and literature survey are given, then in the second part, combined power plants, plant characteristics and flow chart are presented. In addition, for energy and efficiency analysis the relevant equations are explained. In the third chapter, the obtained results are discussed. Finally, the conclusions are expressed in the fourth chapter.

## 2. Material and methods

### 2.1. Combined power cycle plants

One of the plants using fossil fuels is natural gas CCPPs. These natural gas CCPPs are an electrical energy production plant in the world and especially in developing countries. The blocks of the studied natural gas CCPP is illustrated in Fig. 1a. Additionally, a detailed block diagram for CCB1 is presented in Fig. 1b.

Natural gas CCPPs are more efficient compared to single-cycle power plants because they keep at low level the amount of fuel to be used for energy production. In combined cycle systems, as well as being provided cycling of GT with burning fuel, the water, which is heated in the HRSG and transformed to steam with the heat of the released exhaust gases, is sent to ST as hot steam and this provides cycling of ST. Thus, with the fuel burned to cycle the GT, energy is generated from the generators connected to both GT and ST. This increases the amount of energy production and thus increases the efficiency of the combined cycle system.

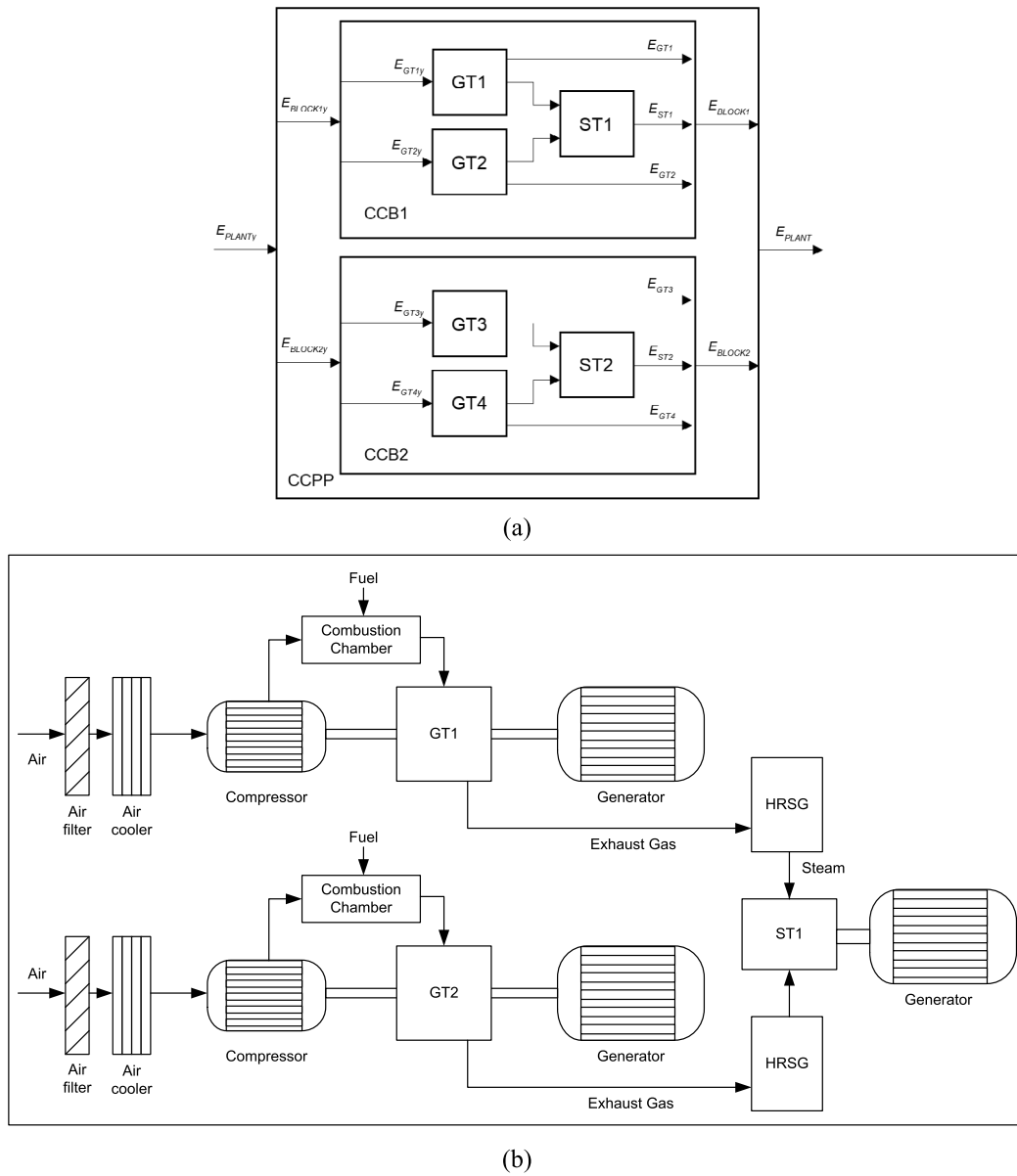
CCPPs are sensitive to ambient conditions, mainly ambient temperature, atmospheric pressure, and relative humidity. In this experimentally study, the ambient temperature is taken into account because it has the greatest effect on the power output power.

### 2.2. Characteristics of the studied natural gas combined cycle power plant

In this study, the electric energy production efficiency of the natural gas CCPP is considered according to the ambient temperature. The natural gas CCPP is installed Aliğa, İzmir, Turkey. Its first installation power is 240 MW. The CCPP is given in Fig. 2. This natural gas CCPP consists of two combined cycle blocks (CCPs: CCB1 and CCB2), each consisting of two GTs, two HRSGs and one ST in each CCP. The models of the GTs used are the GE LM6000 and the models of the STs are Thermodyn 8-10MC10.

### 2.3. Equation

It is important to be able to meet the power demanded by CCPPs. The electricity generation of the power plant should be monitored continuously. Efficiency changes due to fuel, environment and equipment should also be calculated so that it can be estimated how much energy can be met. For this purpose, the



**Fig. 1.** The studied natural gas CCPP (a) blocks and (b) a detailed block diagram for CCB1.



**Fig. 2.** The HABAS studied natural gas CCPP in Aliğa, İzmir, Turkey.

The released energy in a combustion gas resulting from a natural gas CCPP ( $Q_{Gy}$  - kcal/h) is proportional to the amount of fuel consumed per hour ( $B_y$  -  $m^3/h$ ) and the instantaneous thermal value of the fuel ( $H_y$  - kcal/ $m^3$ ) and is given by the following equation:

$$Q_{Gy} = B_y \cdot H_y \quad (1)$$

According to the measurements made in the studied natural gas CCPP, the natural gas of 1  $m^3$  carries 9564.208 kcal energy. Here, 1 kW is calculated as 860 kcal. The amount of energy released in kW ( $E_{Gy}$  - kWh) is expressed as follows:

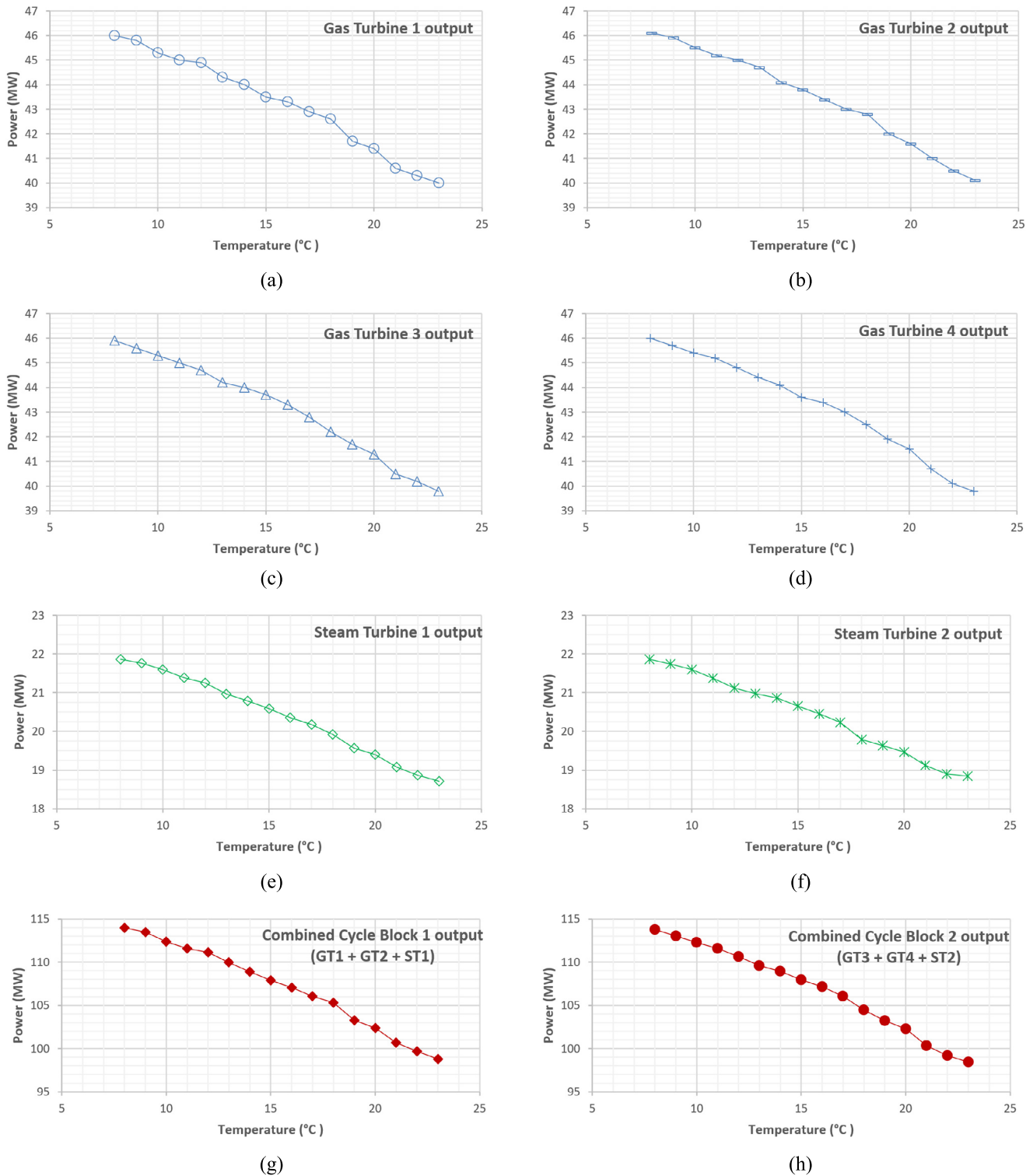
$$E_{Gy} = Q_{Gy}/860 \quad (2)$$

There are four GTs and two STs in the studied natural gas CCPP. The amount of electric power generated from these is given as  $E_{GT1}$ ,  $E_{GT2}$ ,  $E_{GT3}$ ,  $E_{GT4}$ ,  $E_{ST1}$ , and  $E_{ST2}$ .

The yield value obtained from a GT ( $\eta_{GT}$ ) is described as follows:

$$\eta_{GT} = E_{GT}/E_{Gy} \quad (3)$$

following equations are needed to calculate the energy efficiencies of a CCPP.



**Fig. 3.** GT, ST, CCB electric energy generating: (a) GT1, (b) GT2, (c) GT3, (d) GT4, (e) ST1, (f) ST2, (g) CCB1 and (h) CCB2.

In the studied natural gas CCPP, a CCB called CCB1 consists of two GTs and one ST. Accordingly, the total energy generating of CCB1 ( $E_{BLOCK1}$ - kWh) is given as follows:

$$E_{BLOCK1} = E_{GT1} + E_{GT2} + E_{ST1} \quad (4)$$

Similar to CCB1 in CCB2, it is made from two GTs and one ST. In this case, the total energy generating of CCB2 ( $E_{BLOCK2}$ - kWh) is

described as follows:

$$E_{BLOCK2} = E_{GT3} + E_{GT4} + E_{ST2} \quad (5)$$

After combustion, these energies released from GTs ( $E_{GT1y}$ ,  $E_{GT2y}$  - kWh) are a part of the input energy quantities of the natural gas CCPP. Therefore, the input energy amount of GTs in CCB1 ( $E_{BLOCK1y}$  - kWh) is given as follows:

$$E_{BLOCK1y} = E_{GT1y} + E_{GT2y} \quad (6)$$



The total of the input energies of the other two GTs in CCB2 ( $E_{GT3y}$ ,  $E_{GT4y}$ , - kWh) also are the input energy quantities of GT of CCB2. The total amount of the obtained CCB2 input energy ( $E_{BLOCK2y}$  - kWh) is expressed by the following equation:

$$E_{BLOCK2y} = E_{GT3y} + E_{GT4y} \quad (7)$$

The efficiency of the CCBs ( $\eta_{BLOCK}$ ) is expressed as follows:

$$\eta_{BLOCK} = E_{BLOCK} / E_{BLOCKy} \quad (8)$$

Depending on the amount of energy produced by each block ( $E_{BLOCK1}$ ,  $E_{BLOCK2}$  - kWh), the total amount of energy produced in a natural gas CCPP ( $E_{PLANT}$  - kWh) is given as follows:

$$E_{PLANT} = E_{BLOCK1} + E_{BLOCK2} \quad (9)$$

When the input energy quantities obtained from the fuel in each CCB in the natural gas CCPP ( $E_{BLOCK1y}$ ,  $E_{BLOCK2y}$  - kWh), the total amount of energy, which is released as the input energy in the power plant, is calculated ( $E_{PLANT}$  - kWh) is as follows:

$$E_{PLANTy} = E_{BLOCK1y} + E_{BLOCK2y} \quad (10)$$

When the energies obtained in each of the CCBs constituting the plant ( $E_{BLOCK1}$ ,  $E_{BLOCK2}$  - kWh) and the released energies of both CCBs to after the combustion ( $E_{BLOCK1y}$ ,  $E_{BLOCK2y}$  - kWh) are known, the total power plant efficiency ( $\eta_{PLANT}$ ) is found with the following equation:

$$\begin{aligned} \eta_{PLANT} &= E_{PLANT} / E_{PLANTy} \\ &= (E_{BLOCK1} + E_{BLOCK2}) / (E_{BLOCK1y} + E_{BLOCK2y}) \end{aligned} \quad (11)$$

### 3. Results and discussion

In order to perform the efficient calculations of the studied natural gas CCPP at different temperature values, the necessary data were taken by the transmitters, current, voltage transformers and energy analyzers located in the relevant places of the plant. These values were saved and monitored data acquisitions card (DAQ) and a supervisory control and data acquisition (SCADA) program. By means of the SCADA program, all data were grouped and classified. The energies obtained from the GTs and the STs for at ambient temperatures 8–23 °C were calculated and measured based on the equations and sensors. These were presented in Table 1. Depending on the differences between the calculated and measured values, the energy and exergy analyzes of the system were carried out. However, only the effects of temperature on system performance are given here.

The electrical energy generating of GT1, GT2, GT3, GT4, ST1 and ST2 constituting the natural gas CCPP are given in Fig. 3. Additionally, in Fig. 3, the electric energy generating of CCB1 and CCB2 blocks are presented.

When Fig. 3 is analyzed in detail, depending on the sensor data of the natural gas CCPP in GTs, maximum electrical energy of 46 MW was obtained from GT1 at 8 °C. When the ambient temperature reached 15 °C, the electric energy obtained from the GT1 reduced to 43.5 MW. When the ambient temperature reached 23 °C, the electric energy of 46 MW at 8 °C drops to 40 MW, although input was provided to generate maximum power at all temperatures between 8–23 °C via the GT1 controller. This situation was also observed in other GTs. For GT2, electric energy generating at 8 °C was 46.1 MW, it was obtained as 43.8 MW at 15 °C and 40.1 MW at 23 °C, respectively. The electrical energy obtained from the GT3 is measured as 45.9 MW, 43.7 MW and 39.8 MW at 8 °C, 15 °C and 23 °C, respectively. In GT3, for ambient temperature increase of 15 °C, a decrease value was shown of 6.1 MW. GT4 has close values to other GTs. Its electric energy generating at 8 °C is 46 MW. When it reaches at 15 °C, the generated power is 43.6 MW. When the ambient temperature reaches at 23 °C, despite the value

of the controller input for the highest electrical energy generating, its electric energy generating was recorded as 39.8 MW. A decrease of 6.2 MW realized.

When the data obtained from all GTs were examined, almost all GTs given the electric energy generating of 46 MW at ambient temperature of 8 °C. When the ambient temperature reached at 23 °C with an increase in temperature of 15 °C, the decrease in the electrical energy generating by them was approximately 6 MW.

The produced vapor using the CCBs, which have the exhaust gases obtained from these GTs, the combining exhaust gases were formed the input energies of the STs. In other words, the input energies of the STs were realized by the output exhaust energies of the GTs.

HRSG1 and HRSG2 systems were connected to the outputs of GT1 and GT2 in CCB1. The hot exhaust gases obtained from the combustion in the combustion chambers of the GT1 and GT2 are the inputs of the HRSG1 and HRSG2 systems. Here, the water is heated and pressurized into hot steam, and is the input energy of ST1. Therefore, changes in the electric energy generating in the GT1 and GT2 affect the electric energy generating in the ST1.

The electrical energy obtained from ST1 was 21.9 MW when the ambient temperature was 8 °C. When the ambient temperature reached to 15 °C, electrical energy generating reduced to 20.6 MW. The outputs of the GTs decreased about 6 MW because of increasing ambient temperature, although the GTs that feed the ST1 was controlled by the controller for maximum power generation at all temperatures between 8–23 °C. The electric energy generating of ST1 was 18.7 MW at ambient temperature of 23 °C.

On the other hand, HRSG3 and HRSG4 systems were connected to the outputs of GT3 and GT4 in CCB2. The exhaust gases of GT3 and GT4 also constituted the input energies of HRSG3 and HRSG4. The hot steam which was heated and pressurized by these systems was given to ST2. Therefore, the electric energy generating of GT3 and GT4 affected the electric energy generating of ST2.

When the electric energy generating of ST2 was examined at 8 °C, the electric energy was 21.9 MW. When the ambient temperature increased a little and reached at 15 °C, the amount of generated electricity was slightly reduced and was recorded as 20.7 MW. Even when control signals were sent with the help of a controller to generate maximum power to the GT3 and GT4 that feed the turbine, when the ambient temperature reached at 23 °C, the electric energy obtained from the ST2 was 18.9 MW. The decrease was calculated as 3 MW.

On the other hand, when electrical energy productions of CCBs were examined, the variations in the electric energy generations of CCBs were observed depending on the energy generating changes of the GT and the STs. The CCB1 system was formed with GT1, GT2 and ST1. In CCB1, when the ambient temperature was 8 °C, the maximum electric energy was 114.0 MW. The maximum electric energy generating decreased to 107.9 MW when the ambient temperature was at 15 °C. Although the controller input for generating the maximum power at all temperatures between 8–23 °C was provided to the units constituting CCB1, the electric energy generating of 114.0 MW at 8 °C dropped to 98.8 MW at the ambient temperature of 23 °C. As a result, the increase of 15 °C in ambient temperature caused the decrease of 15.2 MW.

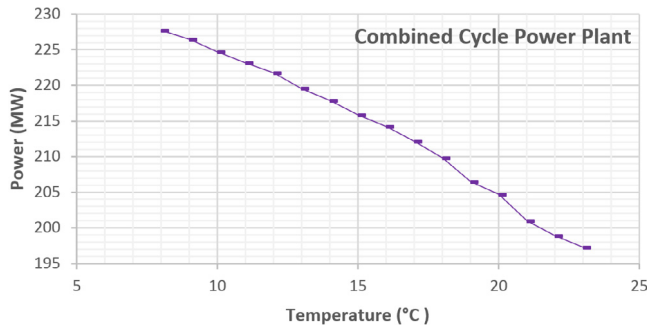
As for the other cycle block CCB2, the electric energy generating was close to the other CCB1 system. This has been introduced in CCB2 from GT3, GT4 and ST2. The electrical energy productions at ambient temperatures of 8 °C, 15 °C and 23 °C were measured as 113.8 MW, 108.0 MW and 98.4 MW, respectively. The temperature increase from 8 °C to 23 °C caused energy loss of 15.4 MW.

The exhaust output of the two GTs in the natural gas CCPP combined to feed an ST. There are two systems in this cycle. These are CCB1 and CCB2. Combined with these, a combined power conversion plant was established. As a result, the electrical energy

**Table 1**

Power generation values of GT and ST for at ambient temperature 8–23 °C.

Ambient temperature (°C)	Obtained power (MW)						Ambient temperature (°C)	Obtained power (MW)					
	GT1	GT2	GT3	GT4	ST1	ST2		GT1	GT2	GT3	GT4	ST1	ST2
8	46	46.1	45.9	46	21.868	21.86	16	43.3	43.4	43.3	43.4	20.349	20.455
9	45.8	45.9	45.6	45.7	21.76	21.74	17	42.9	43	42.8	43	20.173	20.237
10	45.3	45.5	45.3	45.4	21.592	21.595	18	42.6	42.8	42.2	42.5	19.923	19.783
11	45	45.2	45	45.2	21.388	21.372	19	41.7	42	41.7	41.9	19.567	19.638
12	44.9	45	44.7	44.8	21.25	21.123	20	41.4	41.6	41.3	41.5	19.398	19.466
13	44.3	44.7	44.2	44.4	20.963	20.97	21	40.6	41	40.5	40.7	19.08	19.125
14	44	44.1	44	44.1	20.786	20.869	22	40.3	40.5	40.2	40.1	18.869	18.904
15	43.5	43.8	43.7	43.6	20.588	20.654	23	40	40.1	39.8	39.8	18.71	18.846

**Fig. 4.** Electrical energy generating of natural gas CCBP as a function of the ambient temperature.

generating of the studied natural gas CCBP is shown in Fig. 4 as a function of the ambient temperature.

Since the output power of the natural gas CCBP consisted from the CCB1 and the CCB2 blocks, the electric energy generating variations of GTs of the CCB1 and CCB2 affected to the natural gas CCBP. When the data in Fig. 4 were analyzed, the electricity energy output of the natural gas CCBP was determined as 227.7 MW at 8 °C. Even though the output powers of all the units that make up the natural gas CCBP were adjusted to the maximum power output by the controllers, this output value decreased as the temperature increases. It was from 215.8 MW at 15 °C to 197.3 MW at 23 °C. There was a 30.4 MW decrease.

The amount of fuel going to the combustion chamber for each GT in the combustion reaction ( $B_y$ ) was measured by flow transmitters in the fuel line. At the same time, the thermal value of the fuel used ( $H_y$ ) was confirmed by BOTAS.

As the ambient temperature changes, the amount of oxygen in the air of the unit volume varies. Since the difference in the amount of oxygen is effective in the combustion reaction occurring in the combustion chamber, the amount of fuel entering the combustion chamber is being adjusted by the control system of the GTs. The GT control system performs this operation via closing and opening the fuel valve with a proportional valve.

The input energies of GT1, GT2, GT3 and GT4 are calculated with (1) and (2), depending on the amount of fuel that has come into the combustion chamber ( $B_y$ ) and the thermal value of the fuel passing ( $H_y$ ) through it. The energy values ( $E_{GTy}$  - kWh) released from the fuel entering the combustion chamber for temperature values between 8–23 °C as a result of calculations and measurements were found. Burning the fuel in GTs, the energy was released. This amount of energy is part of the input energies of the ST. These values are obtained from (6) and (7) ( $E_{BLOCKy}$  - kWh). Input energy changes of GT1, GT2, GT3, GT4, CCB1 and CCB2 depending on the measured and calculated values are shown as in Fig. 5.

When Fig. 5 is examined, the input energy of the GT1 was 131.4 MW when the ambient temperature was 8 °C. When the ambient temperature increased to 15 °C, the controller of the GT1 tried to regulate the fuel entering the combustion chamber and measured

the input power of 124.7 MW. At an ambient temperature of 23 °C, the GT1 control system continued to fuel the combustion chamber further and the energy released in the combustion chamber of the GT1 was recorded 114.8 MW with a reduction of 16.6 MW. In GT2, while it had an input energy of 131.6 MW at 8 °C, at 15 °C the controller tried to adjust by reducing the fuel entering the combustion chamber and the input power was measured as 125.6 MW. When the ambient temperature reached to 23 °C, this input power was further reduced and the power reduced to 115.5 MW. The input energy for the GT3 was 131.5 MW, 126.1 MW and 115.7 MW, respectively for 8 °C, 15 °C and 23 °C. The input energy of the GT4 in CCB2 was measured at 131.4 °C at 8 °C and 115.9 MW at an ambient temperature of 23 °C with a reduction of 15.5 MW.

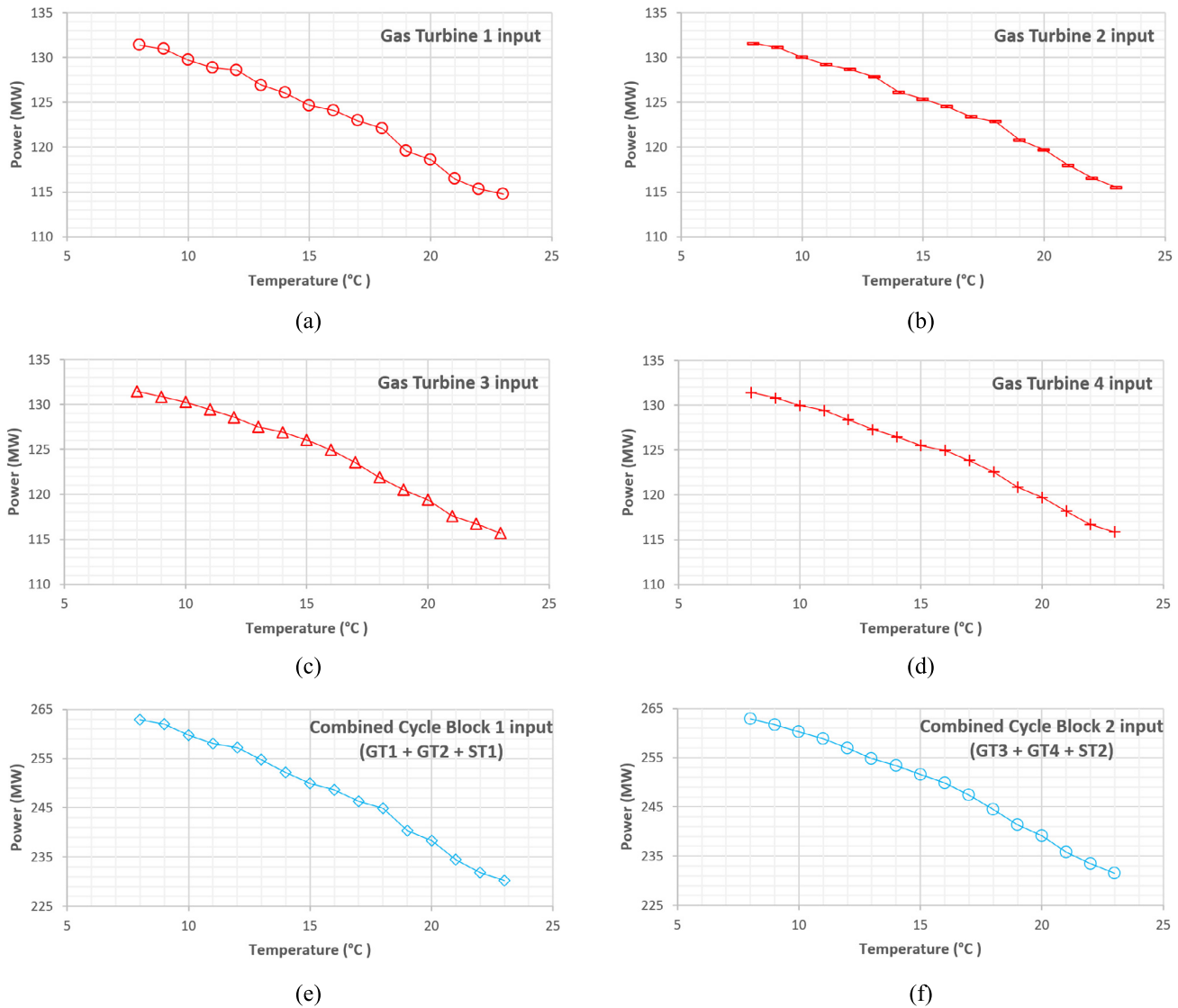
When GTs are considered collectively, the input power of almost every one at 8 °C was 131 MW. Their input power values decreased with temperature increase and were measured as about 115 MW. A decrease of 16 MW was observed when rising the temperature from 8 °C to 23 °C.

On the other hand, these drops in the energy input values of the GTs caused the input energies of CCB1 and CCB2 to decrease. In CCB1, the input energy was measured as 262.9 MW and 230.2 MW for 8 °C and 23 °C, respectively. The fall in input energy was about 32.7 MW. In CCB2, the total input energy to the open combustion chamber at 8 °C was 262.9 MW and 231.6 MW with a reduction of 31.3 MW at 23 °C.

As a result, the studied natural gas CCBP energy input ( $E_{PLANTy}$  - kWh) was obtained by the total energies of CCB1 and CCB2 units. The input energy of the natural gas CCBP was found to be 525.8 MW at 8 °C and 501.6 MW at 23 °C with the aid of (10). The ambient temperature increase from 8 °C to 23 °C caused a reduction of about 24.2 MW at the input power of the natural gas CCBP. The energy input of the natural gas CCBP change is shown in Fig. 6.

The efficiency of GTs and CCBs that make up the natural gas CCBP is presented in Fig. 7. These energy generating efficiency values were met by division the amount of electricity generated in each the ratio of the energy obtained from the fuel that is used to generate electricity and by being expressed as a percentage.

With the ambient temperature increase, the energy output of 46 MW at 8 °C dropped to 40 MW at 23 °C in the GT1, despite the command to generate maximum power. The energy released from the fuel entering the combustion chamber at 8 °C was 131.4 MW, and at 23 °C it was 114.8 MW. The control system of the GT2 is equipped with temperature transmitters and gets ambient temperature information. Since the amount of oxygen in the unit air is reduced as the temperature increases, the control system attempts to reduce the amount of fuel entering the combustion chamber so as to prevent excess fuel from entering the combustion reaction and to prevent it from being thrown out. By doing so, the efficiency was tended to stabilize but the efficiency decreased from 35.0% at 8 °C to 34.9% at 23 °C. Despite the increase in ambient temperature in GT2, the electric energy generating at 46.1 MW at 8 °C declined to 40.1 MW at 23 °C, despite the command to generate maximum power to GT2. The energy released from the fuel entering the combustion chamber at 8 °C was 131.6 MW, and



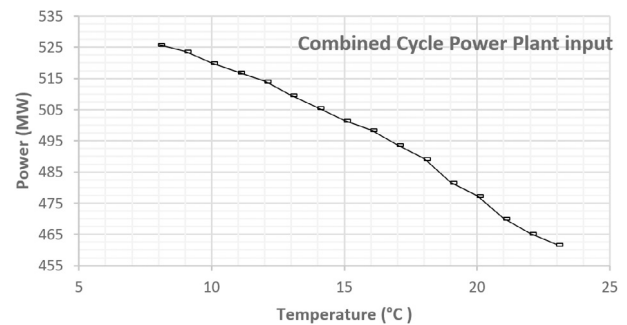
**Fig. 5.** The input energy changes for GTs, STs, CCBs: (a) GT1, (b) GT2, (c) GT3, (d) GT4, (e) CCB1 and (f) CCB2.

at 23 °C it was 115.5 MW. Depending on these, the electricity production efficiency of GT2 was calculated as 8 °C and 23 °C, 35.0% and 34.7%, respectively. The electricity production efficiency of the GT3 was also close to that of the GT1 and GT2 and dropped with the increase of the ambient temperature. These values were found to be 34.9% for 8 °C and 34.4% for 23 °C. The efficiency of GT4 in CCB2 was also 35.0% and 34.4% for 8 °C and 23 °C, respectively.

Efficiency calculations were made for CCBs. The efficiency values of CCBs were significantly affected by the efficiency changes of GTs. The hot gas obtained from the outputs of the GTs was reused in the HRSGs by heating the water into hot pressurized steam. This increased the efficiency of the system. In the studied power generation system, these increased the efficient values of each CCB. As a result, the minimum efficient value of CCB1 at 8 °C was 43.3%, while this value was 42.9% at 23 °C. Whereas for CCB2 it was 43.3% and 42.5% for 8 °C and 23 °C, respectively.

The efficient of the natural gas CCPP was also dependent on the efficient of GTs, STs and CCBs, being consisted by them. The total system was calculated as 43.3% at 8 °C and 42.7% at 23 °C, depending on the obtained ambient temperature and the obtained data. For the studied natural gas CCPP, the efficient, which varies depending on the ambient temperature is shown in Fig. 8.

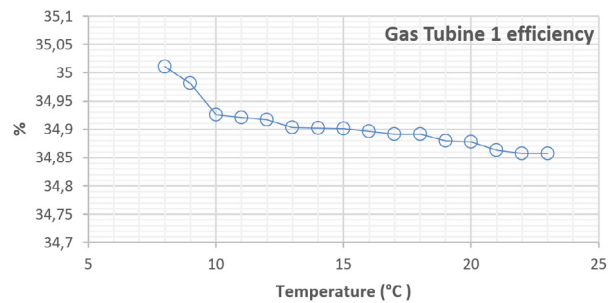
All of these results show that the decrease in the amount of oxygen in the air entering the combustion chamber is the reason



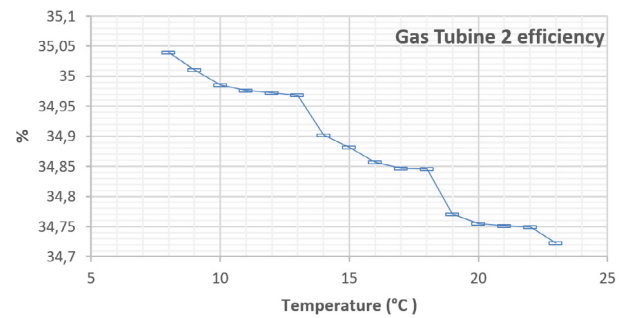
**Fig. 6.** The natural gas CCPP energy input.

for the decrease due to the increase in the efficiency of the natural gas CCPP. If the amount of fuel entering at the low air temperature is applied to the combustion reaction when the temperature of the incoming air is high, the reaction cannot be performed in full efficiency as the oxygen contained in the reacted unit volume of air is low. As a result, neither the desired amount of energy is released nor the unburned fuel is discharged as waste in the combustion reaction. This leads to an increase in the amount of natural gas used

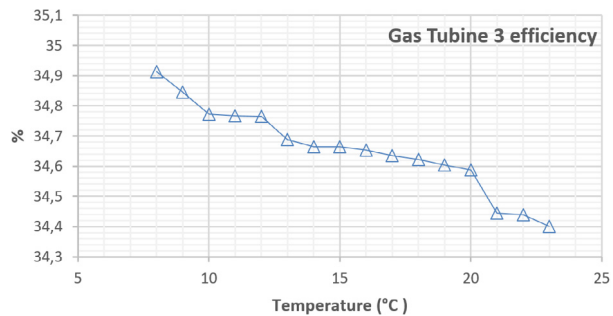




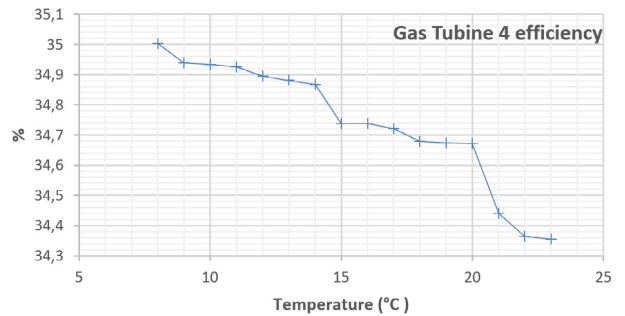
(a)



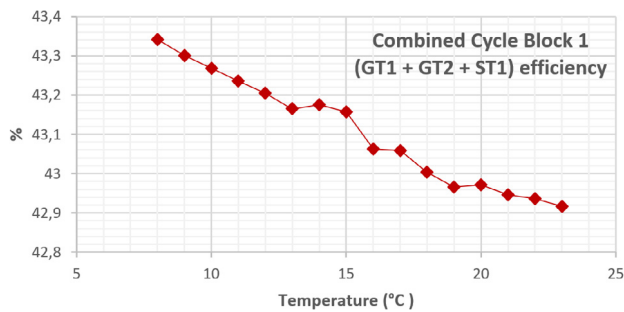
(b)



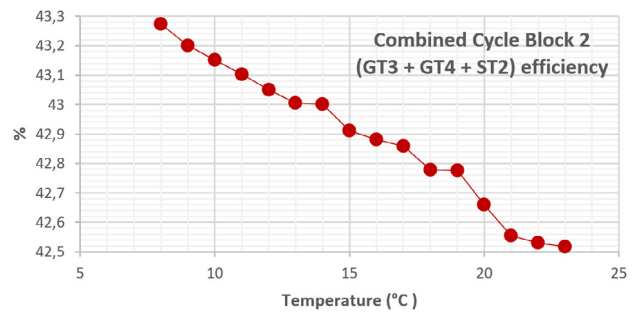
(c)



(d)



(e)



(f)

Fig. 7. GTs and CCBs efficiency: (a) GT1, (b) GT2, (c) GT3, (d) GT4, (e) CCB1 and (f) CCB2.

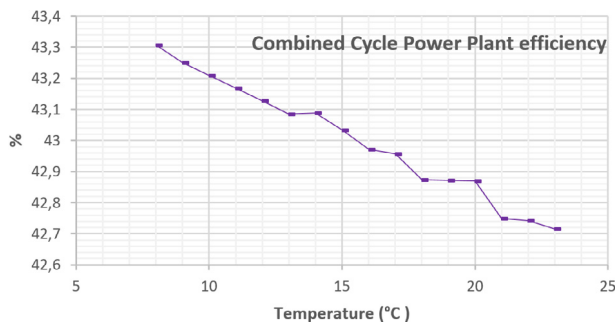


Fig. 8. Depending on the ambient temperature for the natural gas CCPP.

as input energy. In another respect, hydrocarbons are formed out of combustion due to oxygen and the natural gas imbalance. These situations increase both costs and reduce the efficiency.

Data were recorded with DAQ from the installation of this combined cycle power plant until nowadays. When the system was first installed, it reached 240 MW at 8 °C, which is the ideal operating temperature. The daily of electric power generating is

227.7 MW maximum. The decline in the generating of this electric energy was due to erosion dependent on time in the system. These erosions can be generally expressed as mechanical and thermal fatigue. Time dependent abrasion losses, occurring working under pressure in the compression ratios in turbines also affect too. Moreover, the soot formed in the combustion chambers, turbine blade abrasion, chilling in the cooling system and corrosive effects play an important role in decreasing efficiency.

#### 4. Conclusions

In this study, the changes in electric energy production of HABAŞ natural gas CCPP, which has an installed capacity of 240 MW, depending on the temperature, were examined using real data recorded for about fourteen years. Electricity energy generating at 8 °C of natural gas CCPP was 227.7 MW, while electric energy generating at 23 °C was calculated as 197.3 MW with a decrease of 30.4 MW. Depending on the seasonal temperature change, the efficient value was determined as 43.3% at 8 °C and 42.7% at 23 °C. At measurements made between 8–23 °C; although the controllers in the GTs are programmed to generate maximum power, the energy generating of the GTs is reduced as the air temperature increases. These reductions are proportional to the amount of oxygen in

the air of the unit volume entering the combustion chamber. The temperature of the air entering the combustion chamber decreases the amount of residual oxygen, which affects the combustion response. Less burnout leads to less energy availability. Although the control systems of the GTs attempt to protect the efficiency by controlling the fuel entering the combustion chamber, the efficiency decreases as the ambient temperature increases in the GTs. In order to prevent the production and productivity loss in sites in which the air temperature is high and variable, the inlet air temperature has to be kept an optimum value. For this reason, special cooling systems should be installed the CCPPs in such sites.

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